

Khaled bin Sultan Living Oceans Foundation  
**Atlas of Saudi Arabian Red Sea Marine Habitats**

A. Bruckner, G. Rowlands, B. Riegl, S. Purkis, A. Williams, and P. Renaud



*Khaled bin Sultan*  
**Living Oceans**  
Foundation

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Red Sea Marine Habitats

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Front cover: Aerial view of a section of the Farasan Islands. Image by Herb Ripley.

Back cover: Aerial view of nearshore islands in Al Wajh Bank. Image by SpecTIR.

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This Atlas is the result of a collaborative four-year research project between the Khaled bin Sultan Living Oceans Foundation and the Saudi Wildlife Commission (SWC); the Regional Organization for the Conservation of the Environment of the Red Sea & Gulf of Aden (PERSGA); Kingdom of Saudi Arabia; Ministry of Agriculture; Marine Fisheries Department (MFD); the National Coral Reef Institute (NCRI); NOVA Southeastern University; the International Union for Conservation of Nature (IUCN); and Cambridge Coastal Research Unit, University of Cambridge.

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# Preface

This Atlas represents one of the main products generated from four years of research along the Red Sea coastline of the Kingdom of Saudi Arabia by the Khaled bin Sultan Living Oceans Foundation in conjunction with several government and academic partners. The main goals of this project were to map shallow marine habitats off the Saudi Arabian Red Sea coastline and characterize their structure, composition, and condition and provide the resulting information and tools to relevant government agencies in Saudi Arabia as a baseline for future management and conservation initiatives, groundtruthing surveys, and research efforts focused on the Farasan Islands (2006), Ras Qisbah (2007), Yanbu and Al Wajh regions (2008), and the Farasan Banks (2009). The areas were chosen because they represent the most complex marine environments in the region, with shallow habitats often extending 30-100 km offshore. Other less complex areas are not included in this Atlas, primarily because these are dominated by fringing reefs located close to shore that drop quickly into deep water.

This Atlas builds on an earlier study commissioned between 1998-99 by the Japan International Cooperation Agency (JICA) and the Saudi Wildlife Commission (SWC). The former study produced habitat maps of 1:10,000 scale for the northern Red Sea coast of Saudi Arabia, prepared through analysis of aerial color photographs and groundtruthing. Prior to this work, marine surveys and expeditions in the Red Sea started as early as 1761 with the work of *Arabia Felix* (Danish) (1761—67), followed by other several expeditions, namely: *Vitiaz* (USSR) 1886-89; *Valdivia* (GER) 1898-99; *Pola* (Austria) 1895-98; *A. Magnaghi* (Italy) 1923-24; *Snellius* (GER) 1929-30; *Mabahiss* 1933-34 and 1934-35; *Albatross* (Sweden) 1948; *Manihine* 1949 and 1952; *Calypso* (Greece) 1955; *Atlantis* and *Vema* (USA) 1958; *Xarifa* (Austria) 1961; *G. Challenger* (USA) 1971; *Valdivia* (GER) 1971-72; *Sonne* (GER) 1997; *Meteor* (GER) 1961, 1999, 2002; *Urania* (Italy) 2005; *Oceanus* (KAUST) 2008; *Aegaeo* (KAUST) 2010; *Poseidon* (KSA & GER) 2011; and *Aegaeo* (KAUST) 2011—ongoing.

These historical explorations were mainly designed and executed with the principle aim of collecting biological samples for natural history museums. The work of the Foundation is different and more sophisticated, combining satellite-based multispectral sensors, aircraft-based hyperspectral sensors, boat-based echosounders, and state-of-the-art scuba assessments.

The available equipment in the research ship, *Golden Shadow*, including dedicated laboratory facilities and an embarked amphibious aircraft, *Golden Eye*, has allowed extensive aerial hyperspectral surveys of coral reef ecosystems and other state-of-the-art surveys. Remote sensing is the foundation upon which this Atlas is built. Remote sensing is the science of acquiring information about an object or surface without

direct physical interaction with it. In the simplest case (passive remote sensing), a sensor detects reflected or emitted electromagnetic radiation from natural sources, such as the Sun. The best example is a photograph, typically created by a camera, which uses a lens to focus visible light reflected off of an object onto a light-sensitive surface. More involved technologies, so called active approaches, require a signal to be emitted and then a return signal measured. Radar is such an example, where an electromagnetic pulse is emitted by the instrument, and the energy reflected back off of the target is subsequently recorded.

Remote sensing approaches used in this study include satellites, aircraft, boat-mounted tools, and diver-operated tools. Each instrument has its own inherent advantages and disadvantages. Used judiciously, the fusion of these remote sensors provides the basis for accurate shallow seafloor mapping in tropical coral reef environments. Field data collection, commonly referred to as “groundtruthing,” was necessary to facilitate the production of robust and regional-scale coral reef maps with a high degree of accuracy. Data acquisition focused on water depth soundings, optical measurements, and accurately located habitat census. Geographic positioning, through use of differential Geographic Positional System (GPS) technology provided the means to link remote datasets with information collected on the ground.

All fieldwork was carried out using the 67 m *M/Y Golden Shadow*, and its various support vessels, generously donated by HRH Prince Khaled bin Sultan of the Kingdom of Saudi Arabia. The *Golden Shadow* is a safe and highly capable vessel for accessing remote reef environments. A hydraulic platform that can be submerged and raised clear of the water and numerous other lifts, facilitate the rapid deployment of a fleet of small boats.

It is hoped that the information contained herein will be incorporated into marine spatial planning and ecosystem management plans for the coral reefs of Saudi Arabia. These maps provide landscape-scale guidance to decision makers on the location and diversity of habitats and possible locations to target for management. In addition, the maps form a basis from which to assess future changes to these habitats resulting from coastal development, restoration, and the impacts of climate change. It is important to treat these habitat maps as living documents. The authors and the Khaled bin Sultan Living Oceans Foundation would be delighted to incorporate new and revised information into updated printings of the Atlas.

**Andrew W. Bruckner**, BSc, MS, PhD  
Chief Scientist, Khaled bin Sultan Living Oceans Foundation  
May 2012

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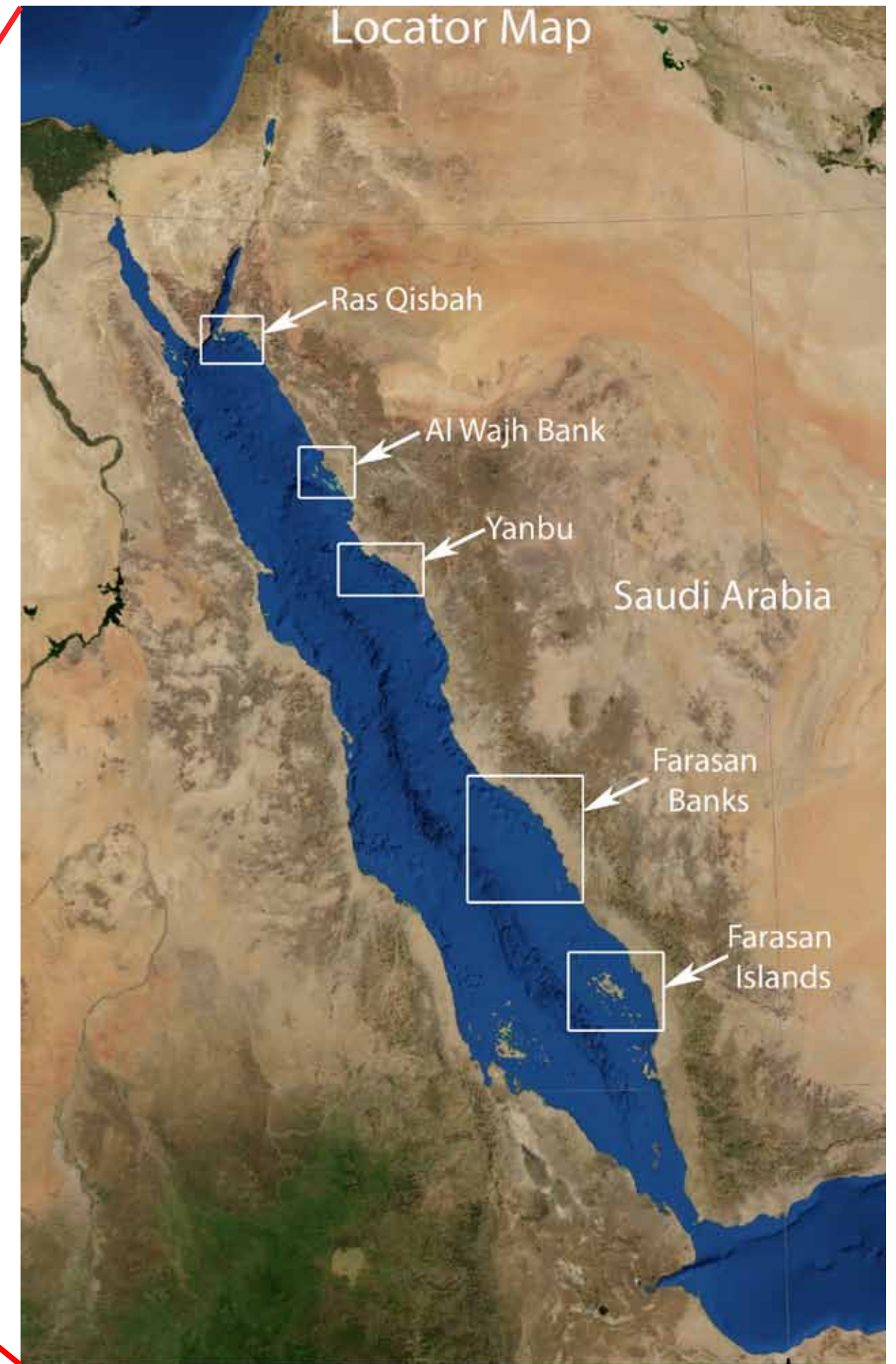
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Message from  
**HRH Prince Khaled bin Sultan**  
Chairman and President  
Khaled bin Sultan Living Oceans Foundation

The Kingdom of Saudi Arabia is blessed with the magnificent Red Sea and its bountiful resources of coral reefs, fish, and marine mammals. Breathtaking beaches and coastline stretch for eighteen hundred kilometers along the western shore of the Kingdom defining the very shape of our nation. Considering our historical connection to the sea, much of what lies below the surface has remained a mystery until now. During the past century, a number of marine scientists have explored portions of the Red Sea. Their studies revealed that the Red Sea ecosystem is far more complex than first imagined and that unraveling the intricacies of the underwater environment would require an entirely new approach.

In response to this urgent need for information, the Khaled bin Sultan Living Oceans Foundation has completed an intensive four-year survey of the most prominent offshore reef structures in the Red Sea. Our scientists employed advanced technologies and an ecosystem-wide approach to study areas such as Ras Qisbah, Al Wajh, Yanbu Barrier Reef, the Farasan Banks, and the coral reefs surrounding the Farasan Islands.

In this context, I am pleased to present this Atlas of Saudi Arabian Red Sea Marine Habitats, the first of its type ever to be published. It represents the culmination of years of scientific research and mapping, extending from the Gulf of Aqaba in the northern Red Sea to Saudi Arabia's southern border.

As you will notice, the coral reefs that exist along the Saudi Arabian coastline of the Red Sea stand out as natural treasures. They can provide great value to our economy. We have a duty to provide knowledge to reef managers so they may work to safeguard our marine ecosystems for future generations. I am certain that the wealth of scientific information contained within this atlas represents a giant stride towards enduring coral reef management and I encourage all of you to take steps toward that noble goal.



Khaled bin Sultan

Message From  
**CAPT Philip G. Renaud, USN(ret)**  
Executive Director  
Khaled bin Sultan Living Oceans Foundation

This Atlas is a product of months of fieldwork in the remote waters of coastal Saudi Arabia and years of data processing. We combined sophisticated remote sensing technologies (satellite and aircraft sensors) with field surveys to create the habitat maps within this Atlas. These high-resolution maps open up a world of possibilities for use in coastal zone management, resource monitoring, future scientific research, and other uses limited only by imagination. The full power of the habitat maps is represented by a Geographic Information System (GIS) database we have developed that requires specialized software, computer systems, and training; whereas, this Atlas serves a valuable purpose in facilitating common access to the maps.

Much of the Red Sea is characterized by narrow coastal fringing reefs that only extend a short distance from shore. The Khaled bin Sultan Living Oceans Foundation did not map the fringing reefs, because their structure is well known and accessible from shore. We concentrated our resources on mapping more complex, offshore reef structures distributed along Saudi Arabia's Red Sea coastline. Of special note are the coral reefs of Al Wajh and the Farasan Banks. Al Wajh is unique in that the area contains all types of marine habitats, including extensive mangrove forests and sea grass beds that serve as critical nursery areas for fisheries species and a barrier reef system bordering its seaward edge. The Farasan Banks area includes the largest number of reef types found in Saudi Arabia and atoll-like structures (tower reefs) found anywhere else on the planet.

My hope is that this Atlas, and other outputs from our Red Sea research program, will be effectively employed to promote the sustainability of the coral reef ecosystems in the Saudi Arabian Red Sea. With a changing climate imposing threats on the health of coral reefs worldwide, it is important to reduce other chronic stress imposed on these ecosystems by man-made development and resource exploitation. Eliminating or minimizing local human stress on reefs will enhance the resilience of these ecosystems to unavoidable climate stress and allow nature to adapt to a changing ocean environment.

Our four-year fieldwork campaign in Saudi Arabian coastal waters (2006-09) was a collaborative effort embracing the Foundation's Science Without Borders® Program. The success of this ambitious project was enabled by remarkable teamwork among the Khaled bin Sultan Living Oceans Foundation, the Saudi Wildlife Commission, the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden, the National Coral Reef Institute (Nova Southeastern University, USA), the International Union for Conservation of Nature, Cambridge University (UK), Saudi Arabian Military Air Defense and Coast Guard, and others. I am indebted to all of our partners for their valuable contributions to the objectives of this project. Special thanks to the capable Captains and Crews of the *M/Y Golden Shadow* and *Golden Eye* seaplane. Ship-based fieldwork requires specialized skills in ship handling and navigation. The *Golden Shadow* was simply the best research ship to achieve the research objectives.

We are all indebted to the vision and generosity of His Royal Highness (HRH) Prince Khaled bin Sultan bin Abdulaziz for establishing the Khaled bin Sultan Living Oceans Foundation and enabling sophisticated scientific research in a quest to rapidly advance scientific knowledge and the application of that knowledge to promote conservation of living oceans.



Philip G. Renaud





# Introduction

The Red Sea is a narrow, but relatively deep, oceanic trough that extends for over 1900 km, between 13° and 28° N latitude. It has a total surface area of roughly 438,000 km<sup>2</sup>, with a width of approximately 180 km in the north, and 354 km at its widest point in the south. The Red Sea narrows to about 29 km in the Strait of Bab el Mandab, where it joins the Gulf of Aden and the Indian Ocean. The maximum depth is over 2200 m, with an average depth of 490 m. The Red Sea is shallowest at the southern end, with depths of only 130 m in the Strait of Bab el Mandab. It is the world's northernmost tropical sea, with extensive shallow shelves that support complex coral reefs and associated ecosystems.

The Red Sea is part of the tropical Indo-Pacific Ocean, which encompasses the largest marine ecosystem on earth and also the most diverse. Much of the Saudi Arabian Red Sea coastline is characterized by coastal fringing reefs that are narrow, extending tens of meters from shore before plummeting to deep water. However, several regions in Saudi Arabia contain extensive seagrass beds, offshore reef habitats, mangroves, and algal flats. These areas support a wide range of reef morphologies, such as barrier reefs, patch reefs, ridge reefs, atolls, tower reefs, pinnacles, pillars, and spur and groove structures, as well as diverse coral communities growing on algal-derived limestone structures (Sheppard et al. 1992).

Unlike some fringing reefs that lack a well-developed reef flat, these regions contain significantly more complex structures that often have reef flats extending seaward up to 1 km or more, and extensive lagoons that may be over 20 m deep located on the landward side of the reef. In the central parts of Saudi Arabia, coral reefs, seagrass beds, and mangroves often coexist. Reef growth along the coast declines markedly to the south, as this area is predominantly a sedimentary basin that is much richer in seagrasses and mangroves, and experiences higher nutrient loading from the Gulf of Aden. There are, however, diverse and well-developed offshore reef systems in the Farasan Banks and Farasan Islands. In the far south, in low energy, sheltered environments, reefs are constructed by calcareous algae. These structures resemble algal ridges found in oceanic, wave-exposed environments, although in Saudi Arabia they arise from a sandy substrata nearshore, in depths of 2-4 m, and develop steep sides. They support dense growths of *Sargassum* spp. seaweeds and only a few sediment-tolerant corals.

The Kingdom of Saudi Arabia contains the largest spatial extent of shallow marine habitats in the region, with an estimated 6660 km<sup>2</sup> of reef area in the Red Sea and western shores of the Arabian Gulf. The Saudi Arabian Red Sea coastline extends from the border with Jordan in the northern Gulf of Aqaba (29°30' N) to the border with Yemen, south of the Farasan Islands (Oreste Point, 16°22' N).

Classic fringing reefs extend southward along the northern Red Sea to 18-20° N, most of which are very narrow, dropping into deep water tens of meters from shore. More extensive offshore reefs are found in the northern



**The Red Sea is flanked by Africa on the west and Asia on the east, stretching from the Sinai peninsula to the Gulf of Aden.**

Red Sea in an area known as the Al Wajh Bank. This area contains an extensive series of submerged limestone platforms that support seagrass, reef, and mangrove habitats. The central Red Sea, in the vicinity of Jeddah, exhibits a wide variety of reef morphologies with extensive reef-flat communities and large lagoons. Fringing reefs are gradually reduced in size to the south of Al Lith (the Farasan Banks), due to an increase in muddy substrates and mangroves. In contrast, the continental shelf in this area is much broader and it supports significant reef development offshore. Further south, around the Farasan Islands, sandy shores, mangroves, and algal flats reach their maximum extent near the coastline, with reefs restricted to offshore locations.

The existence of such a wide variety of reef environments and associated habitats is largely due to the geological events related to the rifting of the Red Sea, which has been ongoing for 30 million years. These events

include uplift, tectonic spreading, rising salt domes, faulting, erosion and alluvial deposition. The severe conditions found in some areas affects the diversity of organisms capable of surviving in these environments. The Red Sea is noted for some of the warmest (exceeding 35°C) and most saline (up to 46 ppt) seawater in the world, partially due to the absence of permanent rivers or streams flowing into the sea, low annual rainfall, and high levels of evaporation. Currents in the Red Sea largely result from density gradients in the water column that vary seasonally due to changes in temperature, prevailing winds, and evaporation. The wind regime is dominated by northwest winds of 7-13 km/hr with regional variations and seasonal reversible winds. Tides vary considerably throughout the Red Sea; central regions around Jeddah experience virtually no difference in tidal heights over a 24-hour period, while considerable daily oscillation is observed in the north (0.6 m) and south (0.9 m).

# Geology of the Red Sea

The Red Sea coast and islands support a variety of coastal and marine habitats that developed largely in response to the oceanographic regime, degree of exposure, and topographic features associated with the distribution of the antecedent topography. The area has a complex tectonic history of uplift and subsidence, related to the rift development of the Red Sea from the movements of the Arabian and African tectonic plates. Living coral reefs, occurring along the Saudi Arabian Red Sea coastline, are the latest in a chronological sequence of raised (uplifted) and submerged reefs that have developed over the past several hundred millennia. In many cases the present reefs are developed on earlier reef structures (Purkis et al. 2010).

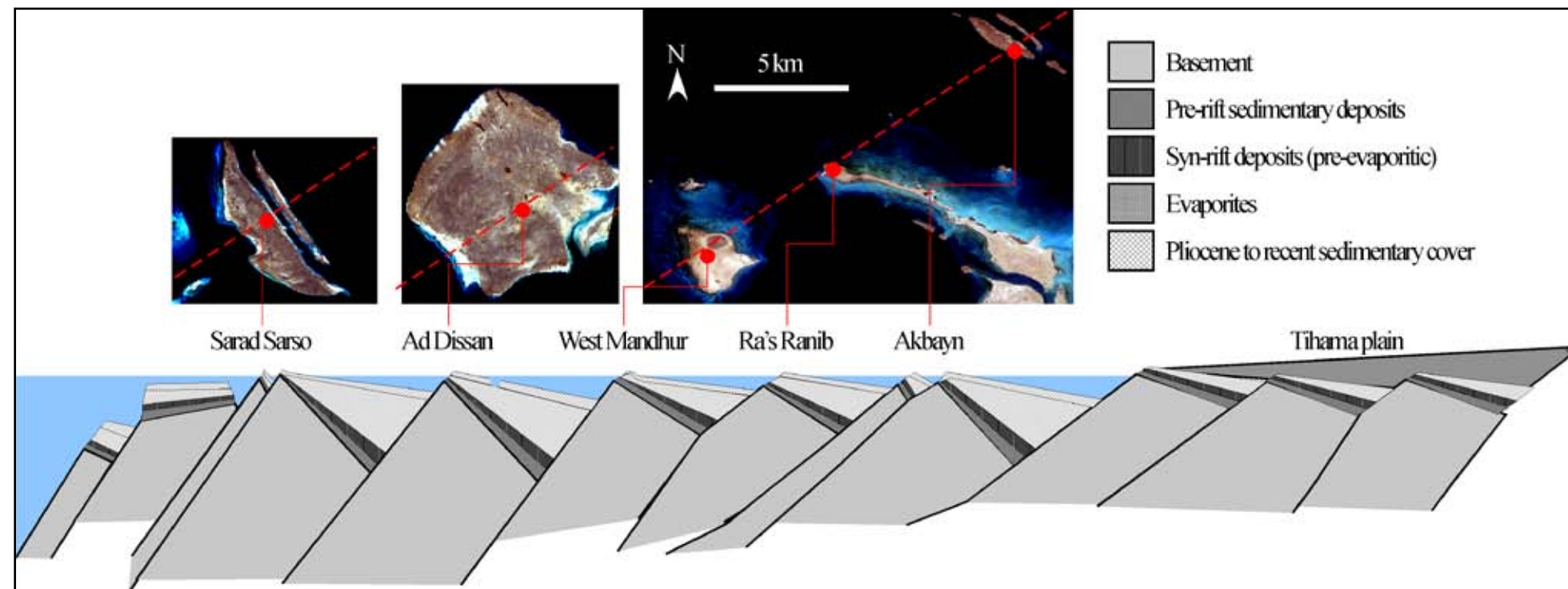
The Holocene Red Sea, i.e. the part of the basin that is presently filled with water, has a total surface area of ~438,000 km<sup>2</sup> and a volume of approximately 250,000 km<sup>3</sup> (Head 1987). It is one of the smallest and narrowest, and clearly incipient, oceans on the planet. The Red Sea is also the youngest ocean, being partly still in, or having just made, the transition from the rifting to the seafloor spreading phase. It is situated between the African and Arabian plates and is a product of their divergence. The African plate is the stable part with north-northeastward separation of the Arabian plate (McClay et al. 1998).

# Tectonic evolution of the Red Sea basin

Although there is uncertainty about the exact mechanism of basin formation, it is known that the development of the Red Sea took place in several stages. All models are in agreement that the last stages of development are those of a small ocean basin with a well-developed spreading center in the southern axial graben. However, the initial stages of development of the main trough remain controversial. It is likely that early rift geometry was causally related to preexisting continental lineaments and crustal evolution during basin-opening (Rihm & Henke 1998). The area likely was a zone of structural weakness as early as 600 million years ago (mya) and was reactivated in the late Oligocene to early Miocene (Chatian-Aquitania) with intense magmatic activity and the development of a continental rift (Makris & Henke 2007). Slow subsidence of up to 1 km occurred over the area during a 100-million-year period before rifting. Initiating in the late Oligocene, thinning of the continental crust was accompanied by the formation of an early “Red Sea–Gulf of Suez” graben. What is today’s Red Sea was then just a series of shallow continental depressions. Along an early transform margin, strike-slip motion created pull-apart basins. This predetermined the steepness of the African margin, which has been conserved through all subsequent phases of Red Sea evolution (Rihm & Henke 1998). Extensional tectonics began to dominate, with slow seafloor spreading from 22 to 15 mya, accompanied by beginning shear along the

Aqaba–Dead Sea transform; the Dead Sea strike-slip fault only experienced intense deformation during the last 14 million years (Makris & Henke 2007).

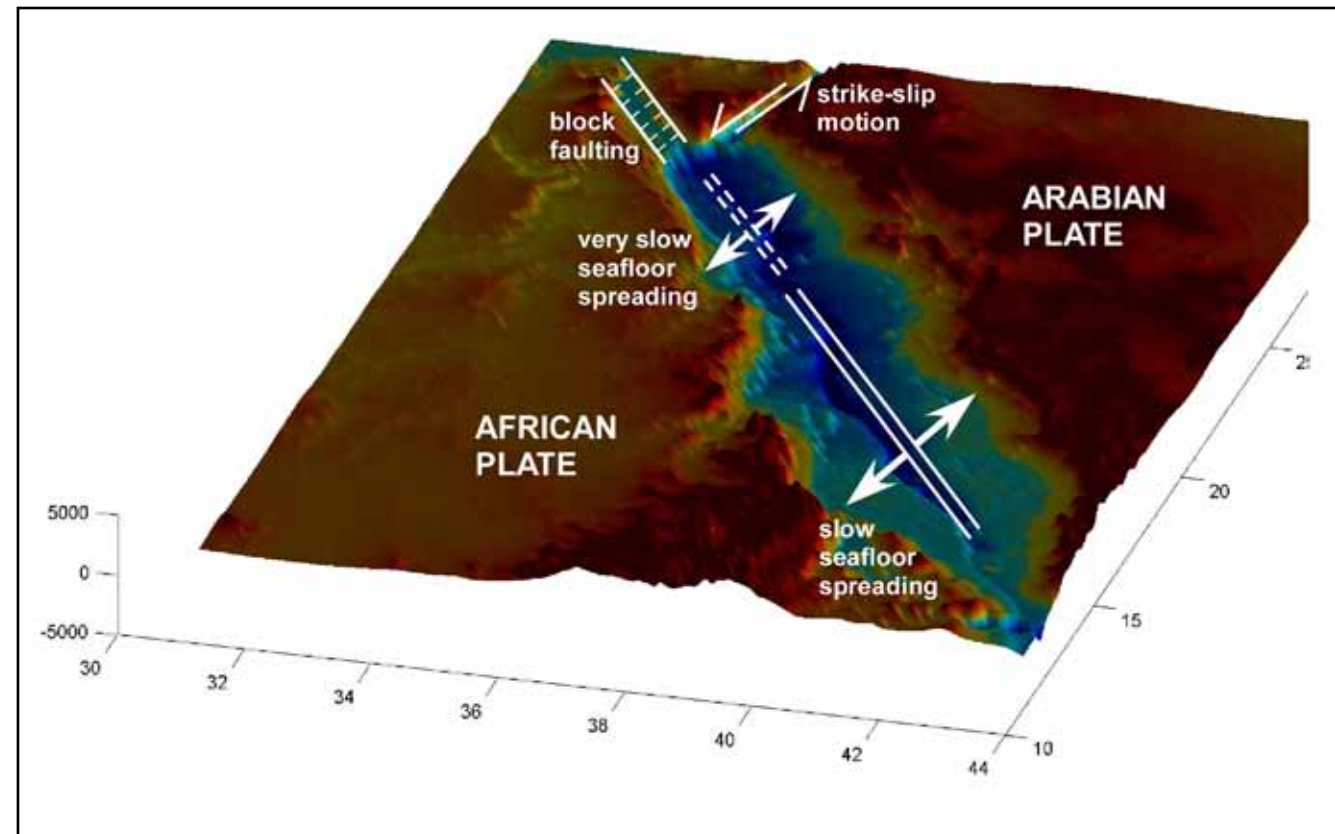
The opening of the Red Sea is linked to upwelling mantle plumes beneath the Afar region (Djibouti, Somalia) that left a clear fingerprint in the pre-rift large igneous province (LIP) in Yemen (31-26 mya). There was a major episode of flood volcanism between ~30 and 20 mya, and important extensional faulting began after the eruption of the volcanic rocks and ceased before middle to late Miocene sediments and volcanic rocks were deposited unconformably on top of rotated fault blocks. Surface uplift has produced the Yemen highlands, whose highest peak reaches an elevation of 3660 m. This is attributed to plume heating and eruption of >3000 m of volcanic rocks (Davison et al. 1994). The rifting phase is characterized by the emplacement of an extensive dike swarm together with plutonic and hyperabyssal rocks at the edges of the basin, found today primarily in Saudi Arabia and Yemen (Chazot et al. 1998). The most recent phase of extension shows slow seafloor spreading in the southern Red Sea from 4.5 mya to present day, accompanied by shear along the Aqaba–Dead Sea transform (Girdler & Southren 1984, Purser & Bosence 1998). Seafloor spreading is still limited in the central and parts of the southern Red Sea (Makris & Henke 2007). The post-rift phase is identified in Saudi Arabia and Yemen by extensive alkaline volcanism (Purser & Bosence 1998). Perim island, at Bab el Mandeb, is an expression of this post-rift volcanism. There exists a very clear gradation in the stage of basin-evolution within the Red Sea/Gulf of Aden region. The furthest along in a post-rifting phase of ocean-floor spreading and drifting are the Gulf of Aden and southern Red Sea; these date from the early Pliocene (~5 mya). The Red Sea proper is in an early post-rift stage with incipient ocean basin formation while the Gulf of Suez is still in the active, syn-rift phase. Not surprisingly, this provides for different tectonic environments that in turn define different sedimentary environments. In particular the formation of shallow areas in the Sea are important for the formation of carbonate platforms and corals reefs. Due to the differing dynamics in the Red Sea, these opportunities are furnished either by fault blocks (e.g., the edges of half-graben in the northern Red Sea and the Gulf) or salt tectonics (e.g., in the southern Red Sea and the wide shelves of the Farasan and Dahlak Islands; Purser & Bosence 1998). Since the Arabian flank moved away from the stable African flank, the former (eastern Red Sea) flank was formed by pure shear through stretching and thinning. Thus, the two flanks are asymmetrical, with the western flank steeper, having inherited more of the original strike-slip morphology; while the eastern flank is more gentle, with a wide assortment of fault blocks.



**Block-diagram of a potential stratigraphic cross-section through the Farasan Islands region. Extensional stresses related to the spreading of the Red Sea basin have led to a series of normal block faults. The positions of the fault blocks can be inferred from the islands, which represent structural highs. Other islands are formed by salt tectonics (not illustrated here).**

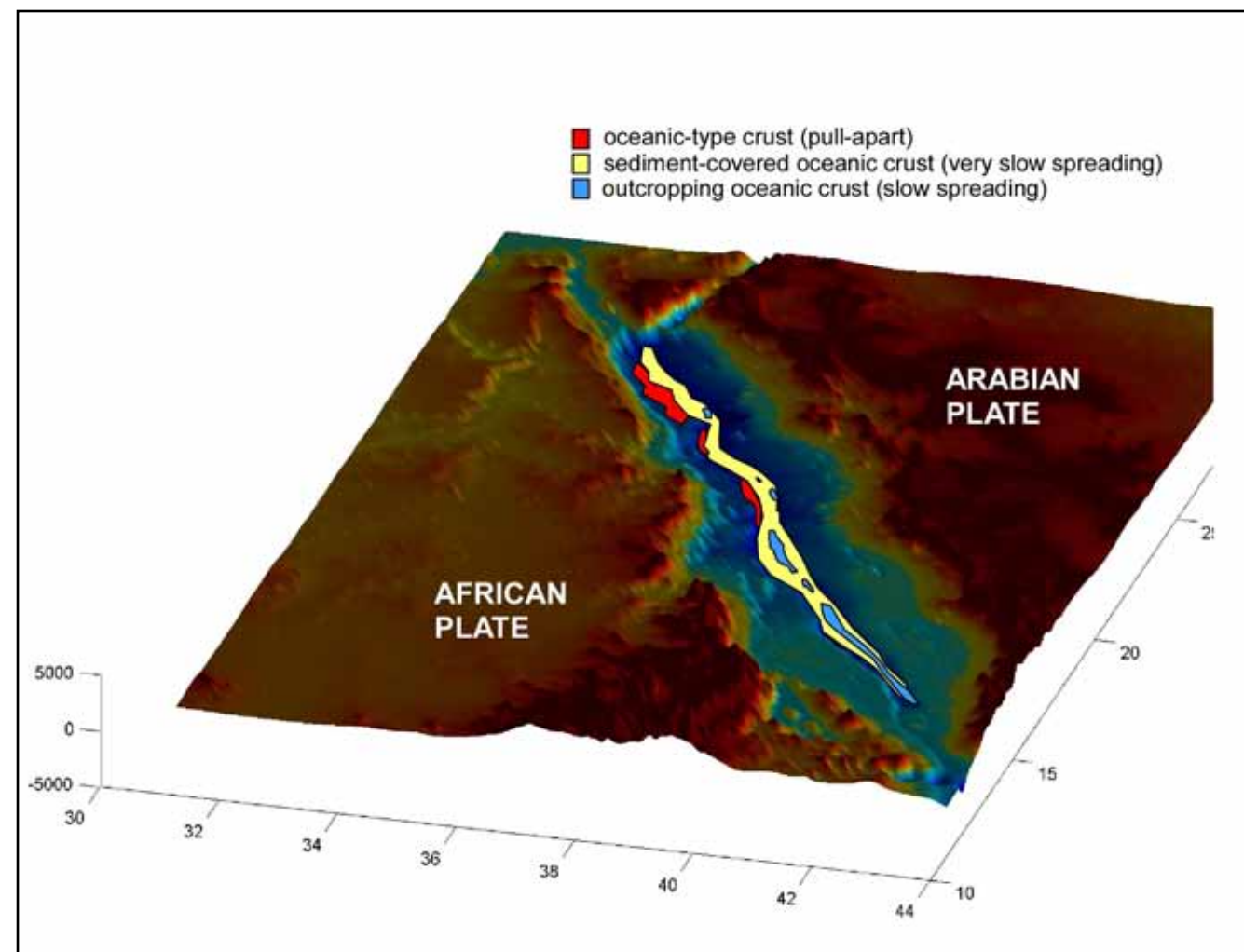
## Oceanographic evolution of the Red Sea basin

The history of ocean spreading is encoded in the types of oceanic crust, while that of the ocean itself in its sedimentary record. In the Late Oligocene-early Miocene (Chattian-Aquitanian) thin, generally continental red beds accompanied by volumetrically minor basaltic volcanism were formed. In the Aquitanian (>20 mya), sedimentation was dominantly shallow to marginal marine with coarse-grained conglomerates and sands at the rift margins and finer grained mudstones and marls toward the center of the rift. Since there are different patterns of faulting throughout the Red Sea, and adjacent fault zones separated by accommodation zones, their detailed configuration and dynamics can differ (Purser and Bosence 1998). Thus, individual fault blocks within the rift system experienced different structural and stratigraphic evolutions. The greatest synrift sedimentation occurred in the Burgidalian (the so-called rift climax, 20-15 mya) with thick accumulations of Globigerina marls and shales in the central rift basins. The following Miocene was a period of abundant reef formation in the Red Sea and large, well-developed reef complexes are known throughout the Red Sea (Perrin et al. 1998). The fauna of these reefs was dominated by a typically Mediterranean coral fauna (for example by the genera *Porites*, *Tarbellastrea*, *Montastraea*) of 16 genera and 27 species, which is half of the Mediterranean fauna at the time (Perrin et al. 1998). While these reefs formed, there was a wide oceanic connection to the Mediterranean at Suez, while the southern connection to the Gulf of Aden was not established yet. In the late Serravallian to Tortonian (<12 mya) the rift subbasins became isolated from open ocean circulation and thick evaporite deposits were formed, a period called the Great Evaporation. These deposits predate the massive Messinian (~6 mya) evaporitic deposits in the Mediterranean, associated with the Mediterranean salinity crisis, by at least 5 million years and identify the Great Evaporation as an independent event and therewith clearly show oceanographic independence of the Red Sea from the Mediterranean. In many areas of the Red Sea, the chemistry of the deposits (primarily sulfates and halite) suggest a shallow, cutoff basin, that neither fully evaporated, nor was fully restored to normal marine conditions, but was subject to repeated, intermittent evaporation (Braithwaite 1987). These salt deposits can later become mobilized after their deposition and burial. The pressure of newly sedimented overburden and salt tectonic, due to moving salt, is responsible for the formation of many islands and seafloor structures, in particular in the southern Gulf of Suez (e.g., Giftun archipelago; Orszag-Sperber et al. 1998) and the southern Red Sea (Farasan and Dahlak archipelago; Purser and Bosence 1998). In the Pliocene to recent, normal marine conditions prevailed with connection to the Indian Ocean via Bab el Mandeb and the Gulf of Aden (McClay et al. 1998). In the Pliocene, the isthmus of Suez became fully lifted and connection to the Mediterranean was permanently severed. The connection to the Indian Ocean now, for the first time, allowed a typical tropical fauna of Indo-Pacific character to develop in the Red Sea.



Block diagram of the Red Sea basin

**Top:** Type of spreading differs in the northern and southern regions. The Gulf of Aqaba is formed by lateral, strike-slip motion forming a deep basin. The extensional stresses caused by this movement lead to block faulting in the Gulf of Suez region. Thus the Gulf of Aqaba is deep, the Gulf of Suez shallow. Seafloor in the southern Red Sea spreads faster than in the northern Red Sea.



**Bottom:** Differential spreading rates are mirrored by different types of crustal outcroppings. Only in the southern Red Sea is young oceanic crust found outcropping. Due to slow spreading rates in the northern Red Sea, it is there covered by sediment. The oceanic-type crust found in the northern Red Sea relates to a previous spreading episode.

# Climate and Oceanography of the Red Sea

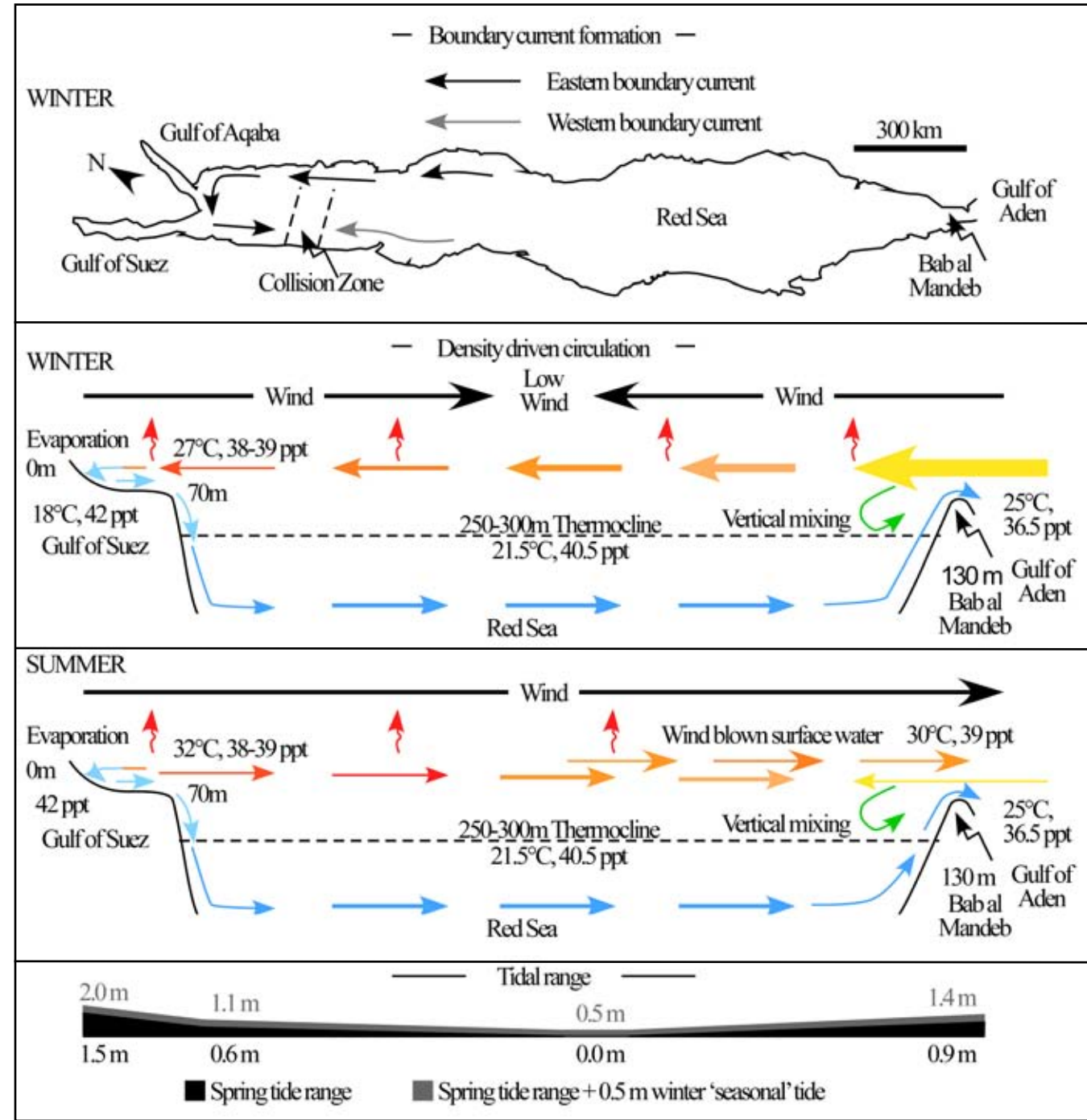
The Red Sea coastline lies at the edge of two global weather systems that fluctuate seasonally, with changes in prevailing winds, rainfall, water circulation patterns, and air temperatures. The arid nature of the region, hot climate, high levels of solar radiation, limited rainfall, absence of rivers, and seasonal variability in wind direction together create some of the harshest environmental conditions found in the tropics, second only to the Arabian Gulf.

The main features of the weather system include:

- 1) Summer winds and associated upwelling off the southern Red Sea,
- 2) Strong winter winds off the northern Red Sea that cause significant evaporation and salinity changes, and
- 3) Changes in local wind patterns responsible for seasonal variations in mean water level by as much as a meter.

## Seasonal climatic cycles and local wind systems

The Red Sea is affected by the Asian weather system that causes two main Indian Ocean monsoons. During winter the Red Sea has two airflows, one from the northwest in the northern Red Sea and a second from the southeast in the southern Red Sea, converging in the center of the Red Sea. The Northeast Monsoon is fully developed during the first quarter of each year, with winds flowing generally from the east and continuing up to about the central Red Sea; the northern Red Sea is not affected by the Northeast Monsoon, and winds flow primarily from the northwest as a result of Mediterranean weather penetrating down the Red Sea. In the second quarter the Southwest Monsoon builds up, with winds flowing primarily down the Red Sea for its entire length. The Red Sea is also affected by daily sea breezes during summer that increase in strength in the afternoon, blowing generally from the northwest. These prevailing winds affect the alignment of coral reefs, which tend to grow into the prevailing waves. Wind patterns also affect the spatial distribution and size of mangrove stands located within embayments.



**Schematic diagram illustrating the predominant direction of water flow due to the boundary current (top), effects of wind and evaporation on water circulation during the winter (top middle), and summer (bottom middle). The bottom figure depicts a cross section of the Red Sea basin illustrating the tidal range associated with a spring tide during summer months and the seasonal increase in the spring tide during winter.**

## Water currents and circulation

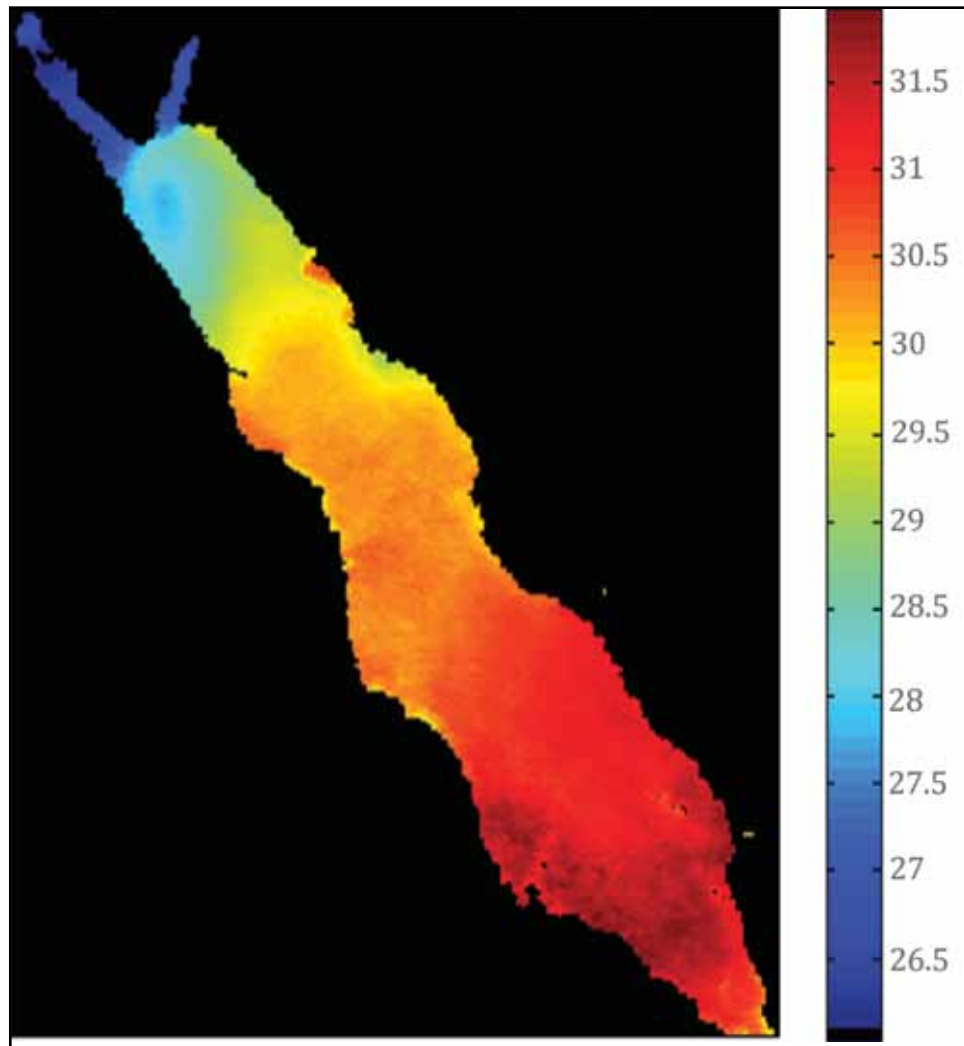
Water circulation patterns in the Red Sea are largely driven by density gradients, with a general tendency for surface waters to flow north and a southward return of dense water below the thermocline at 250-300 m depth. The decline in temperature and high levels of evaporation (1-2 m/yr) in the north can cause increases in salinity of as much as 4 ppt, increasing surface water density. The steep salinity gradient in the Gulf of Suez and marked difference with the northern Red Sea concentrates the dense, cool saline water near the entrance to the Gulf of Suez. As it flows into the Red Sea, it sinks and returns southward below the thermocline (250-300 m depth). There is a net loss of water in the Red Sea due to high levels of evaporation (1-2 m/yr), low precipitation (generally no more than 10 mm/yr), and a loss of water as it flows northward into the Mediterranean, due to differences in tidal height between the Red Sea and Mediterranean. This loss results in a net inward flow of Indian Ocean water through the Bab el Mandeb. In winter, surface water driven into the Red Sea from the Gulf of Aden by prevailing winds has a temperature of about 25° C and salinity of 36.5 ppt, while a deeper outward flow of higher salinity (40.5 ppt) and lower temperature (21.5° C) water from the Red Sea. In summer, there is still inward surface flow and deeper outward flow. However, as the Red Sea heats up, the surface waters become less dense, causing the upper layers to divide into two components, a wind-blown shallowest flow traveling south out of the Red Sea and an inward flowing, cooler water from the Gulf of Aden.

## Waves and tides

Tides in the Red Sea differ dramatically from the Indian Ocean and the Arabian Gulf. The normal tides are small and occur twice a day (semidiurnal tides), oscillating around a nodal point in the center of the Red Sea, approximately at the latitude of Port Sudan. The tidal range increases with distance from the central region, from virtually no daily change to about 0.6 m in the north and up to 0.9 m in the south. Superimposed on the daily fluctuation is a seasonal tide, with mean water levels during summer being about a half meter lower than in winter. The difference is mainly due to greater evaporation in the summer and the result of wind-driven currents in the entrance to the Red Sea.

## Water temperatures

Normal surface water temperatures in all parts of the main basin vary between about 22° C in the winter and 32° C in the summer, with the warmest temperatures between 15°-18° N latitude. Surface temperatures are slightly lower at the southern end near Bab el Mandeb due to the influx of cooler water from the Gulf of Aden. There is also a gradual decrease in temperature as one moves in a northerly direction, reaching the lowest temperature in the Gulf of Suez. The Red Sea is unique among tropical oceans for having an extremely stable warm water temperature throughout deeper waters. Water temperatures are maintained at about 21.5° C from about 250 m to the seafloor everywhere, except where heated brine pools exist. In contrast, water temperatures in all other major oceans drop to below 10° C at these depths.



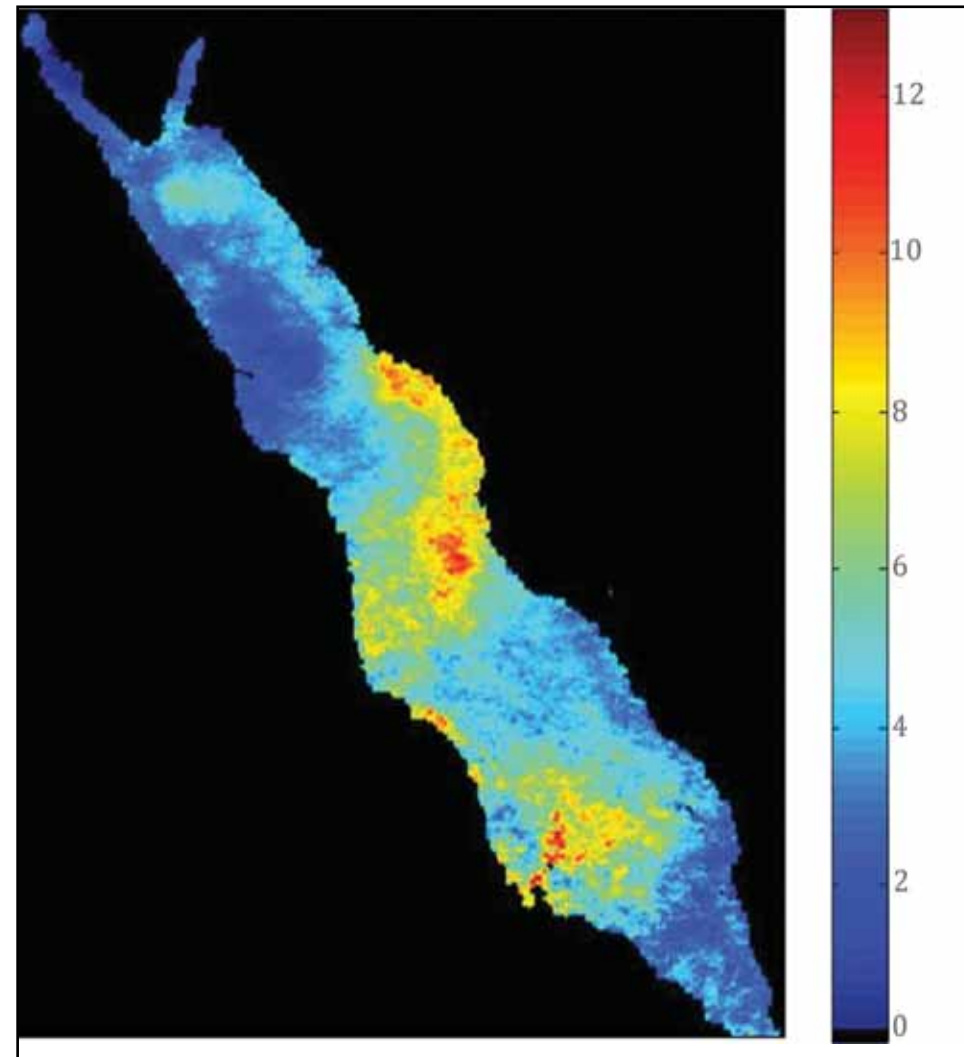
Top: Annual maximum water temperatures at the sea surface in the Red Sea, derived from satellite data, averaged over a 10-year period from 1997-2007.

Right: The average numbers of degree heating weeks experienced by different locations in the Red Sea between 1995-2005. A degree-heating week measures the extent to which weekly temperatures exceed the maximum monthly mean temperature. The average number of degree-heating weeks is analogous to the thermal stress experienced at each location.

## Rainfall, evaporation, and salinity

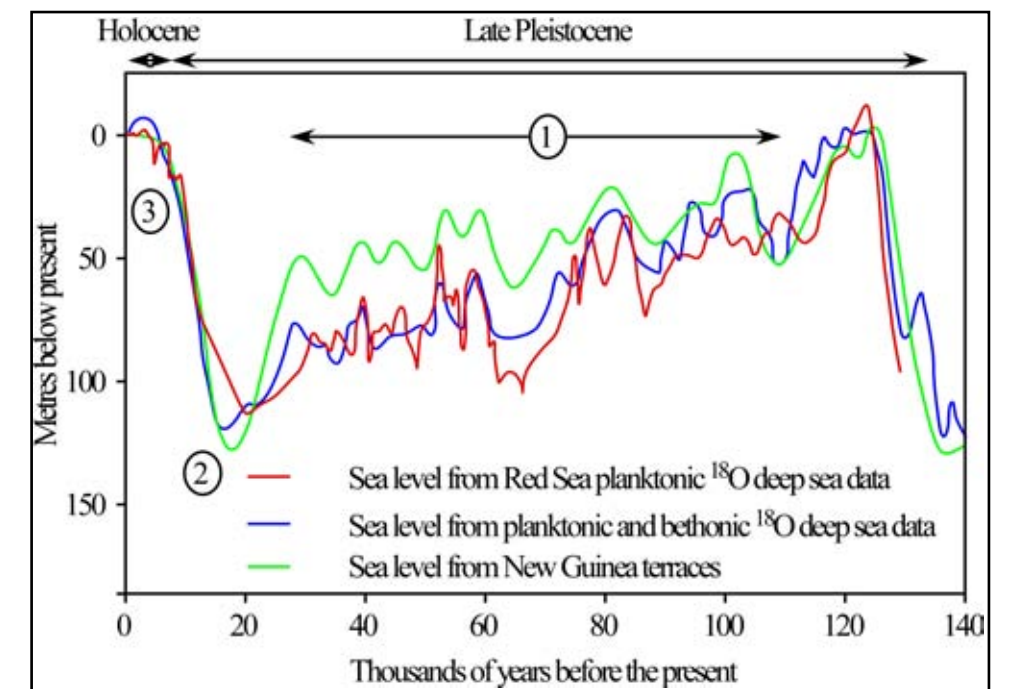
The climate is extremely arid. Average rainfall is less than 70 mm/yr along the broad coastal Tihama plains of the Red Sea (Al Wajh: 16 mm/yr; Jeddah: 63 mm/yr; Jizan: 63 mm/yr). Inland, above the coastal escarpment, rainfall often exceeds 200 mm/year. There are no perennial rivers that discharge anywhere along the Red Sea coast. However, a number of valleys (referred to as “wadis”) originate in the adjacent mountains and terminate at the coast. These collect water from the mountains during occasional floods and bring it to the plains and eventually to the coastal habitats, also carrying alluvial sediments.

Evaporation in the Red Sea averages 1-2 m/yr, continuing in both winter and summer. There is a gradual increase in salinity toward the north, with average salinities of 36.5 ppt at Bab el Mandeb to 40.5 ppt in the north, at the entrance to the gulfs of Aqaba and Suez. Salinity continues to increase in the Gulf of Suez; in winter, when water temperatures drop to below 18° C and evaporation continues, salinities can increase to 42.5 ppt, causing steep salinity and density gradients and marked differences where it converges with the Red Sea and sinks. Overall, there is very little difference in temperature and salinity between surface and deep waters in the northern Red Sea, with increasing differences toward the south.



## Sea level change

The influence of past sea level change has profoundly influenced present day reef biogenesis and erosion. Important features of sea level are: 1) an extensive period in the Pleistocene 110-30 Ka BP where sea level typically fluctuated between 30 and 60 m below present, 2) the precipitous drop in sea level to ~120 m after this period, and 3) the length of time and exact heights of sea level 5 Ka BP to the present (Sheppard et al. 1992). In the period 35-17 Ka BP, the climate was characterized by heavy rainfall leading to sheet flow of alluvial material and huge fans and outwash systems (Purkis et al. 2010). These structures provide important foundations for contemporary biotic and sedimentary systems. Reefs formed prior to this were either smothered and/or scoured following aerial exposure. Low Red Sea levels through the Pleistocene and increased rainfall lead to the potential for wadis to be cut 60-90 m below present levels. The Hanish Sill, the shallowest point in the Bab al Mandeb, is believed to have been exposed during the 17 Ka BP sea level low. Complete closure of the Red Sea from Indian Ocean circulation would have had profound influence on biota. The combination of an arid climate and near – full closure would have substantially increased salinity due to evaporation, causing possible widespread extinction, including hermatypic coral species. Recent Holocene sea level change suggests sea levels rose ~1m above present, about 6 Ka BP, with a slow subsequent fall to present levels (Sheppard et al. 1992).

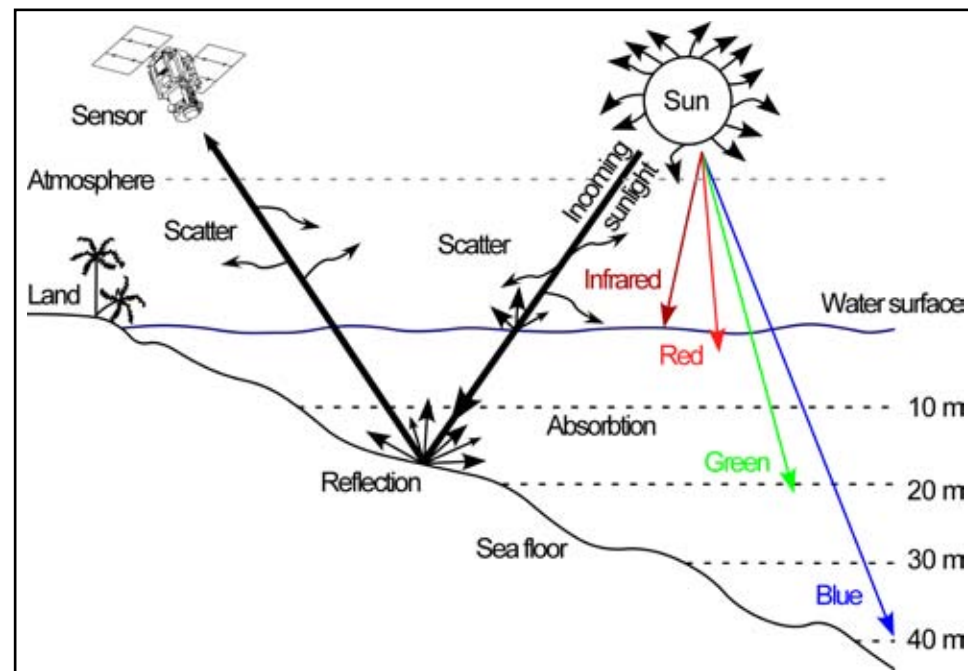


Past sea level reconstruction curve using Red Sea O<sup>18</sup> data calculated from plankton (red) and combination of planktonic and benthonic (blue, Siddall et al. 2003) and sea level curves for the New Guinea terraces (green, Lambeck and Chappell 2001).

# Optical Remote Sensing

The vast majority of the maps presented in this Atlas were produced using images collected from a passive visible-infrared spectrum satellite. To a lesser extent, imagery acquired from aircraft was also used. An optical approach to coral reef mapping has many advantages, including the ability to characterize incredibly large areas with relatively little field effort. Remote sensing techniques are very well suited to study of areas that are difficult to access in-situ. Passive optical remote sensing from satellite and aircraft is a mature technology that represents both a powerful and cost-effective mapping strategy.

Satellite and aircraft images are a record of sunlight reflected off of the Earth's surface. Along its path to the Earth's surface, a large portion of sunlight is scattered by the particles and gases within the atmosphere. Partial reflection, as well as refraction, occurs at the water surface. If this air-water interface is rough, reflection off the surface can be high and penetration of light into the water is low. Referred to as sun-glint or simply "glint," this problem is particularly pronounced if the Sun is low to the horizon or the water surface is rough at the time of image acquisition. By contrast, if the water is calm and clear, and the Sun is high above the horizon, a sizable fraction of the light penetrates the water surface and propagates down toward the seabed. Light is absorbed differentially as it moves through a body of water. Infrared light, that is light with a wavelength between 700 nm and 30,000 nm, is fully absorbed at the water's surface. Red light (600-700 nm) may penetrate a few meters, green light (500-600 nm) around 20 meters, and blue light (400-500 nm) reaches a maximum depth of several hundred meters but is useful in a remote sensing case to depths of only ~40 m.

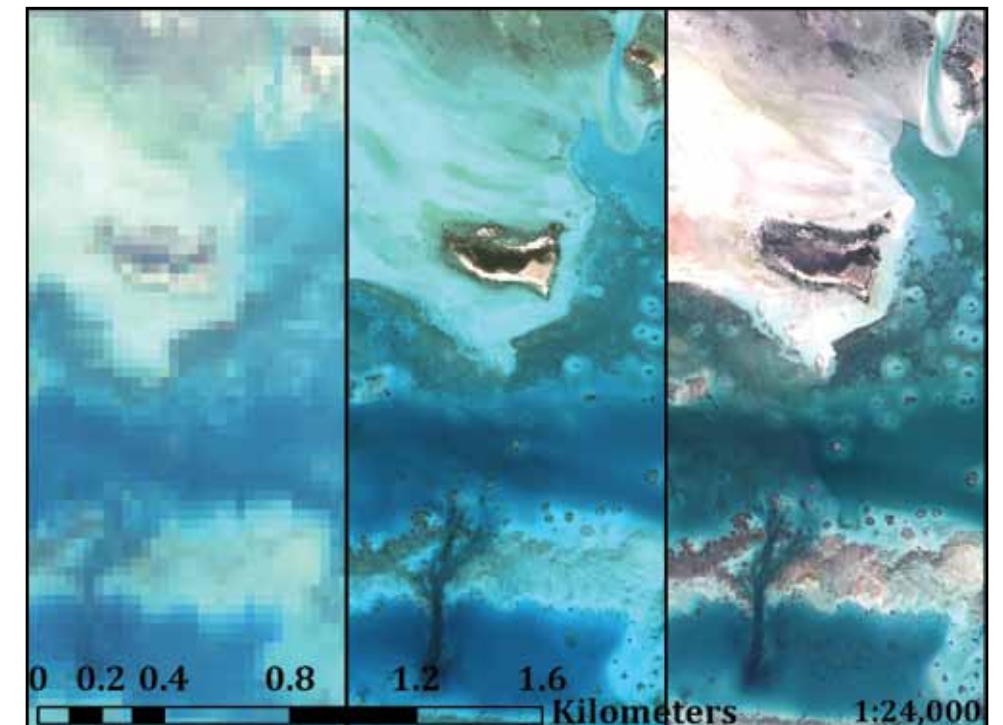


Turbidity in the water column, by virtue of an increased scattering of light from suspended particulates, reduces the depth of light penetration. Remote sensing images taken under extreme turbidity and/or surface roughness are rendered useless for mapping purposes as even the very shallow seabed is obscured. Light energy that passes through the water column interacts with and reflects off of the seafloor. A portion of light, albeit typically only a fraction of that which originally downwelled onto the sea surface, may be reflected upward—back through the water column, water surface, and atmosphere—before being intercepted by an overflying remote sensor. Central to the practice of mapping seafloor habitats, using optical sensors is the fact that different seabed types have different reflectance characteristics. Dense seagrass beds, for example, by virtue of their chlorophyll content, predominantly reflect light in the green portion of the spectrum, while absorbing red and blue light. In contrast, sand has a high reflectance across all wavelengths of visible light, though increases in magnitude toward the red portion of the spectrum. Because light must pass through the atmosphere, surface interface and water column twice on its way from source to sensor, seafloor habitat mapping using optical sensors is constrained to clear, calm tropical waters with a maximum operating depth of approximately 35 m. Imaging sensors may be mounted on a variety of platforms, but typically a satellite or an aircraft is used. Modern instruments used for mapping usually operate in a pushbroom fashion. Sunlight reflected back from Earth is recorded by a linear-array of optical sensors. The resultant digital image is a rectangular grid where each cell, commonly referred to as a "pixel," is characterized by a digital number. This number corresponds to a measurement of the light from a defined area on the ground. The size of area that may be sensed at any one time (the swath width) may be enlarged by increasing the size of the sensor array, raising the altitude of the sensor above the ground, or widening the instantaneous field-of-view of the instrument. As the sensor is raised above its target, however, each pixel in the resultant image becomes larger. Aircraft sensors typically have the highest spatial resolution as they are closer to the target than satellite sensors.

Left: A schematic diagram depicting the fate of photons in shallow tropical water. Only the signal that reflects off the seafloor contains viable information used by the sensor to interpret the benthic character.

An important attribute of optical sensors is the level of spectral detail, or "spectral resolution," they provide. Sensors are commonly characterized as either multispectral or hyperspectral. Multispectral sensors measure light across a handful of discrete portions of the electromagnetic spectrum. Each of these portions is termed a "band." Hyperspectral sensors have several hundred narrow and contiguous bands, such that the entire visible spectrum may be covered in great detail. This increased spectral resolution allows for enhanced discrimination of spectrally similar seabed habitats (such as, the separation of algae from seagrass). Orbiting satellites, which travel at great speed and altitude above the surface of Earth, are typically multispectral. These sensors do not remain over one spot long enough to allow for detailed spectral measurements without sacrificing spatial resolution.

The swath width of imagery acquired from aircraft is considerably smaller than that of a satellite. The same aerial coverage is acquired in seconds by satellite and days by aircraft. Consequently, there is a trade-off of imagery acquisition time (cost) versus spatial and spectral resolution. GPS sensors measure position, while a gyroscope is used to measure pitch, roll, and yaw of the aircraft. Correction for all of these effects is usually carried out by the survey contractor before image delivery. Geopositional accuracy, while high, is typically less easy to obtain as compared to imagery collected using the more stable platform of a satellite.



Comparison of the resolution of imagery of a portion of Al Wajh Bank at a scale of 1:24,000 from Landsat (left), QuickBird (middle) and AISA Eagle (right).

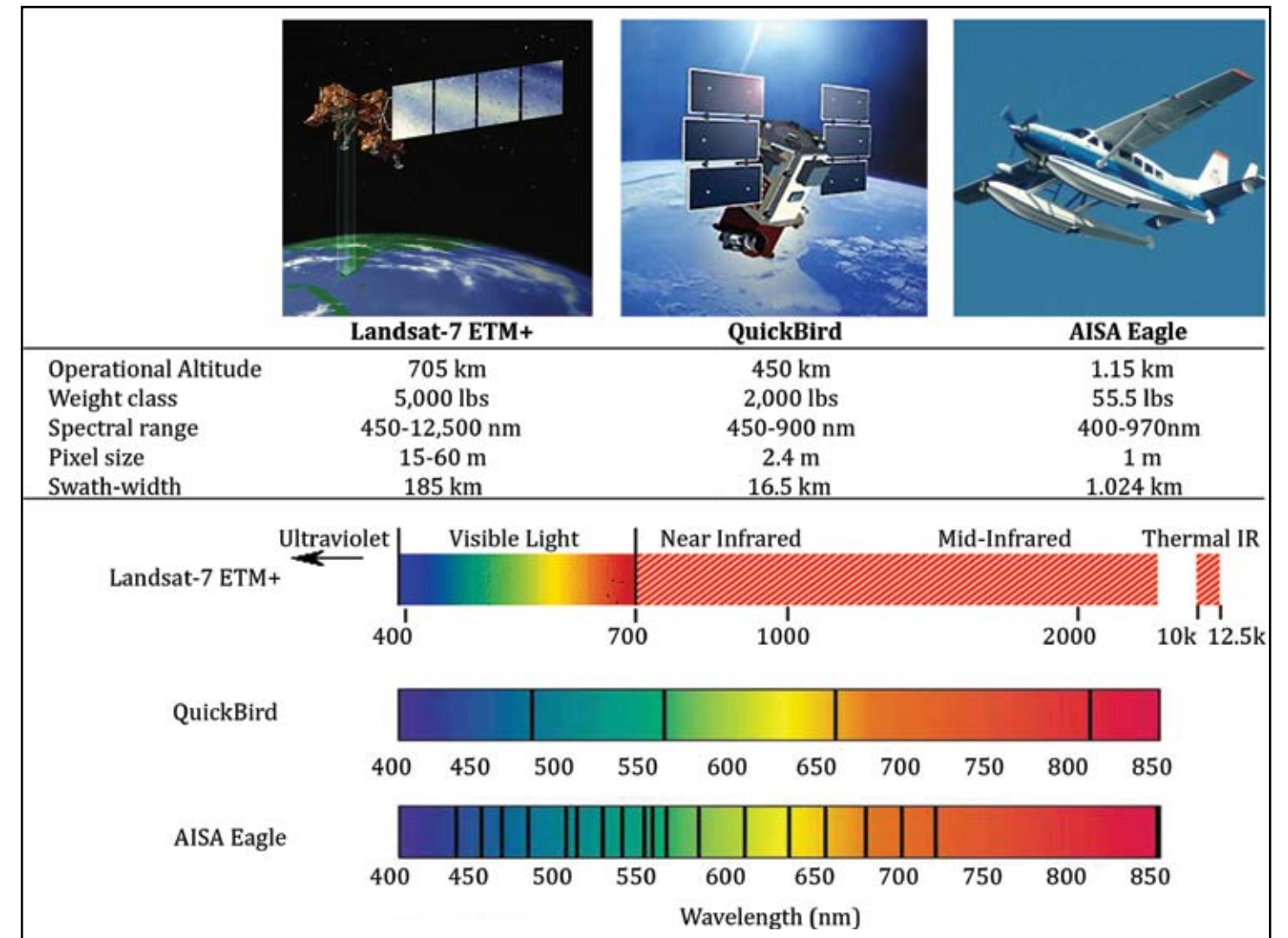
## Optical sensors used for this project

The QuickBird satellite (DigitalGlobe, Inc.) provided the bulk of imagery used for mapmaking in this Atlas. The spatial resolution of QuickBird is around 60 cm (panchromatic) and 2.4 m (multispectral) across a wavelength range of 450-900 nm. Panchromatic refers to a grey scale image derived from a single cross spectrum measurement. The QuickBird orbits every 93.4 minutes at an altitude of 450 km with a 98° sun synchronous inclination. The swath width for each image scene is 16.5 km. A total of 25,000 km<sup>2</sup> of QuickBird imagery was purchased by the Khaled bin Sultan Living Oceans Foundation at 11-bit precision, spanning the length of much of the Saudi Arabian Red Sea coast. Satellite scenes extend from the shoreline to depths of 20-30 m offshore. All of the QuickBird imagery was evaluated for quality prior to purchase. Scenes with excessive sea-surface-glitter, cloud cover, or other factors that obscured seafloor features, were avoided. Imagery was acquired as a georectified product, such that each pixel of the image was assigned a geographical coordinate. Much of the image processing was carried out prior to field deployment so as to enhance data collection.

Landsat *ETM+* (NASA/U.S. Geological Survey) is an older satellite platform launched in 1999, and the final installment of the Landsat Earth Observation program that initiated in 1972. Although Landsat has a coarser spatial resolution of 30 m<sup>2</sup> as compared to QuickBird, the data were used for navigation and site-selection in the field, as well as for habitat classification on occasions where cloud obscures reef features in the QuickBird scenes.

The CASI 550 (Itres Inc.), an aircraft-mounted sensor, was used in the Western Farasan Islands to survey an area of approximately 3,200 km<sup>2</sup>. Flying at an altitude of 1.3 km, data were collected at 1.5 m<sup>2</sup> pixel resolution, with 19 bands assigned between 400 and 660 nm and 2 bands within the near-infrared (NIR) region (700-900 nm), representing a noncontiguous, 21-band hyperspectral dataset. The instrument was mounted on the seaplane.

The AISA *Eagle* (SPECIM Ltd.), also an aircraft-mounted sensor, was used in Al Wajh to survey an area of approximately 2000 km<sup>2</sup>. Data were acquired at a 1 m<sup>2</sup> pixel resolution, with a maximum 244 bands assigned between 400 and 1,000 nm. This represented a continuous hyperspectral dataset spanning the visible and infrared spectrum. As with CASI 550, the instrument was mounted on the Cessna seaplane.



Remote sensing systems used in this Atlas to collect multispectral and hyperspectral imagery. The spectral resolution for Landsat includes three bands in the visible, three in reflective IR range and six in the thermal IR range. QuickBird operates in the panchromatic mode or multispectral mode with a spectral resolution of four bands in the visible region (band centers shown as black lines). AISA *Eagle* operated with 19 bands in the visible (black lines) and two bands within the near IR region.



Acoustic sub-bottom profiler (left) and acoustic depth sounder (right) deployed from survey vessel's side. For the sub-bottom profile, a cable transmits data to a laptop aboard the boat while a second cable stabilizes the transducer during travel along the transect line. The cable for the acoustic depth sounder is housed within the metal pipe that attaches it to the boat.

## Groundtruthing

Groundtruthing is a term that refers to information collected in the field to enable calibration of remote sensing data, and aids in the interpretation and analysis of these data. Compared to the acquisition of remote sensed imagery, groundtruthing is a time-consuming and labor-intensive component of the mapping process. Because of the constraints of time and resources, localized acoustic measurements, photography and tethered-videos of the seafloor were collected at defined points along this acoustic track, and light reflectance measurements were used to ensure that the most crucial information for habitat mapping was collected, while covering as large a geographic area as possible.

Acoustic groundtruthing approaches are powerful tools for reef mapping because water is an excellent medium for sound transmission, and acoustic energy travels much faster and further than in air. Low-frequency acoustic energy can travel deep into the water column as it is not disrupted from its path by suspended particles, thereby allowing effective mapping in both clear-tropical and turbid-temperate environments, to much greater depths than optical sensors. Acoustic tools emit sound waves and time the return of the reflected energy. On encountering a hard surface, such as the seafloor, a portion of the emitted sound energy will reflect back toward the sensor. By measuring the time between the transmission and the return signal, the distance between the transducer emitting the sound and the seafloor can be accurately determined (i.e., the water depth). If a single, as opposed to multiple, beam of acoustic energy is used in the sounding, the technology is simply referred to as "single-beam" sonar. For an accurate depth measurement in shallow water, a transducer emitting an acoustic wave in the 60-210 kHz is typically used, a frequency capable of sounding accurately down to depths of several hundred meters. Acoustic bathymetry soundings are particularly valuable in the calibration of optical algorithms used for the extraction of water depth from multispectral and hyperspectral data.



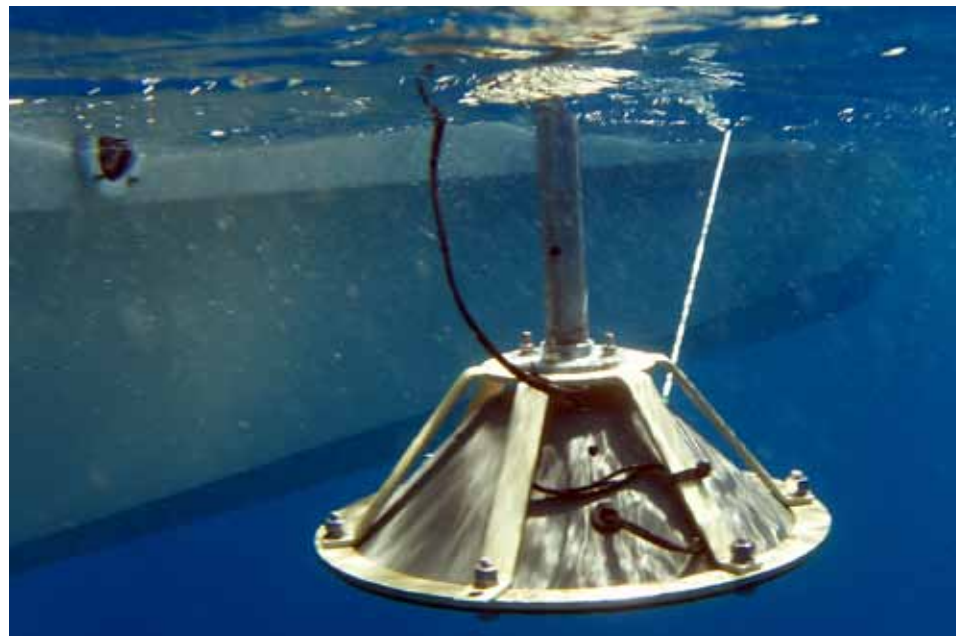
Use of varying frequencies of acoustic energy allows different characteristics of the seafloor to be discerned. Seabed-penetrating acoustics are a single-beam variant that use a very low-frequency acoustic wave in the 3-10 kHz range. This has the benefit of providing a measurement to a greater water depth (800 m +) though at slightly lower accuracy than could be achieved by a higher frequency transducer. Low-frequency sound also is capable of penetrating through the seafloor and down into the underlying rocks and sediments. The pulse of sound reflects off layers beneath the seabed caused by the juxtaposition of different sediment types. By measuring the time taken between the instrument emitting a pulse and receiving the various echoes back, a two-dimensional digital representation of the structure beneath the seabed is generated. For this reason, such an instrument is referred to as a “sub-bottom profiler.” Low-frequency acoustics may also be used to examine the sub-seafloor stratal geometry of a coral reef. Such information is useful for the reconstruction of the growth rate of the reef system through recent geological time. Acoustic technology is typically operated directly from, or towed behind, a ship or small boat. Use of acoustic tools is therefore limited to where these vessels can safely navigate. All acoustic sensors used in this project were operated from a small catamaran capable of accessing very shallow (< 1 m) depths.

### Single-beam sonar

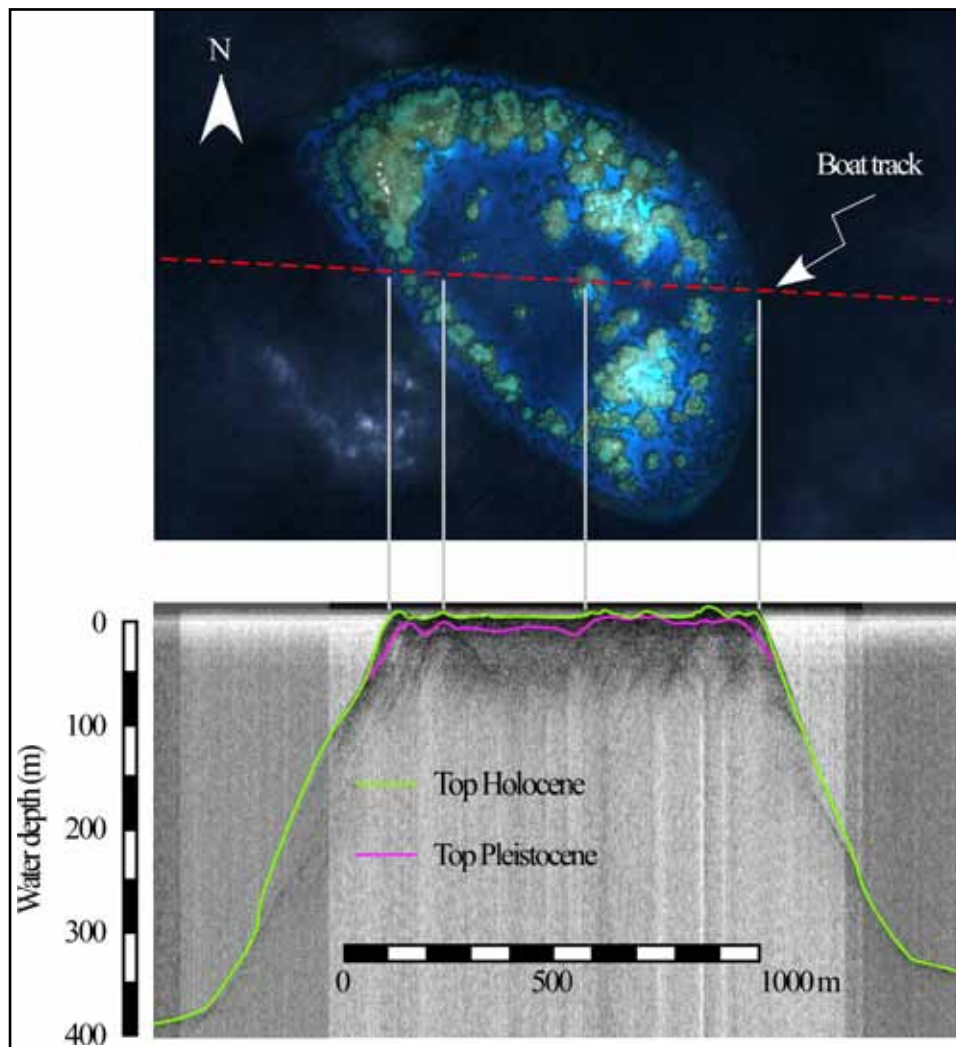
Single-beam sonar is operated vertically, providing depth directly below a vessel. A 200 kHz acoustic echo-sounder was used in mapping Ras Al-Qasabah, Al Wajh, Yanbu, and the Farasan Islands. This emits a sound-pulse five times per second, collecting depth information with an accuracy of  $\pm 0.2$  m to a max operating depth of 60 m. A more advanced hydrographic survey-grade acoustic sounder used in the Farasan Banks also operated over the 200 kHz range, although the instrument emits an acoustic pulse ten times per second and delivers an accuracy of  $\pm 0.1$  m to an operating depth of 200 m. These devices were linked to a high accuracy dGPS unit, and run continuously during the groundtruthing process. Over 2.7 million depth soundings, covering a total 1,400 km of survey track, were acquired for the five locations. The survey vessel’s track was routed to include a range of depth contours across a variety of seafloor types.

### Sub-bottom profiler

Within the Farasan Banks region, a portable sub-bottom profiler was used. The instrument was able to detect different sediment layers at a resolution of 6 cm, with up to 40 m sub-seabed penetration. In addition, the profiler could double as a deep-water depth sounder, providing bathymetry measurements to 800 m with an accuracy of  $\pm 0.5\%$ . To obtain viable sub-seafloor information, either a 10 kHz or 3.5 kHz transducer was used, depending on depth and substrate hardness. Transects were routed perpendicular to slopes, bisecting lagoon systems and other geomorphological features identified from satellite imagery as potentially containing suitable reef structures below the sediment layer.



Deployment of a 10 kHz transducer for stratigraphic surveys.



Top: QuickBird image of an offshore tower reef in the Farasan Banks. The red line is the boat track acquired by a sub-bottom acoustic profiler. Bottom: Image of the two-dimensional cross section through the seabed.

### Photography and videography

Direct observation using photography and videography of the seafloor provides the finest mapping resolution, but proves ineffective tools for observation purposes, even for areas as small as 1 km<sup>2</sup>. Remote Operated Vehicles (ROVs), tethered-video, and scuba surveys all represent viable means of collecting these data. Scuba surveys involving the acquisition of photo-transects were conducted at a selection of sites also parameterized via tethered-video. This was done to ensure that inferences on seafloor character derived from the tethered-camera observations were robust. Reef areas of up to 100 m<sup>2</sup> were mapped to fine detail using underwater photo-transects. Multiple digital photographs collected along transects were stitched together into mosaics two meters wide by 10 meters in length. Photo-transects provided a centimeter-scale audit of substrate diversity used as calibration for the vastly more expansive, yet coarser-scale, satellite and aircraft mapping.

Tethered video cameras were deployed directly from the boat to depths of up to 50 m to better characterize bottom communities and habitat structure. Using dGPS, coupled to navigation software, the survey team worked with the QuickBird satellite imagery in real time to plan and execute the



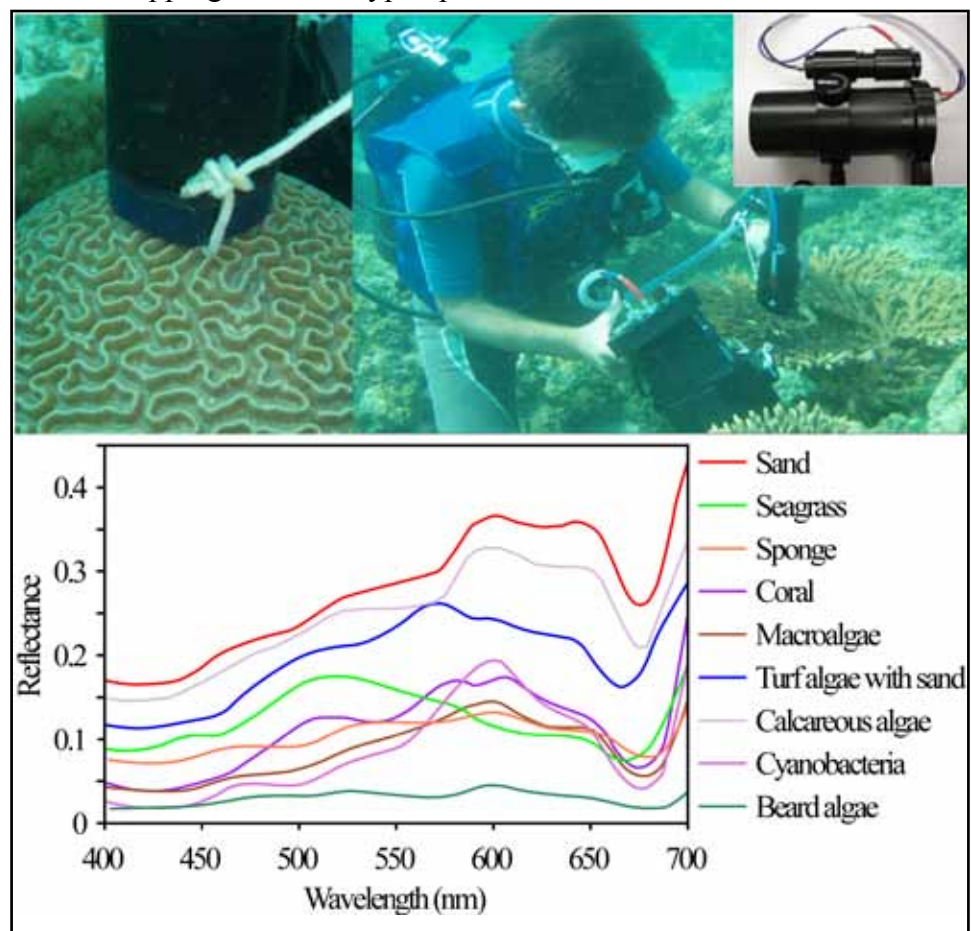
SeaViewer tethered video camera used to characterize habitats.



fieldwork. Careful targeting of features with a tethered-video setup facilitated the acquisition of data of seabed geomorphology and habitat type, while maximizing time-efficiency. At each survey point, a submersible tethered-video camera was lowered and “flown” one meter above the seabed for 10-30 seconds. Over 3,500 individual points were videoed. The movie clips were analyzed and classified into discrete habitat types and used to develop a habitat classification scheme for the region.

## Spectral reflectance measurements

Direct measurements of seafloor reflectance properties allow calibration of remote sensed imagery and the training of processing algorithms. Using a submersible spectroradiometer, measurements of reflectance signatures (the quantity and quality of light reflected off of a small target) from terrestrial and submerged habitat-types were acquired. Reflectance spectra were captured for exposed bright beach sands, the dark deep ocean, live and dead coral, algae, seagrass, and other features that represent the end-members in brightness encountered in the satellite imagery. These measurements, coupled to computer modeling, were used to aid in the atmospheric correction of the satellite and aircraft imagery and to enhance habitat mapping from the hyperspectral airborne scenes.



Using a Divespec, submersible spectroradiometer to measure reflected light from different substrate types. Top left: Positioning the sensor over coral. Top right: Collecting spectra of a coral. Bottom: Spectra collected in Al Wajh over sand, seagrass, sponge, algae, and coral.

## Image preparation

A rather evolved sequence of processing is required to produce an accurate habitat map from a satellite or aircraft spectral image. Among the greatest challenges to resolving seafloor character using optical remote sensing lies in accounting for the considerable attenuation of both the incident and reflected light as it passes through the atmosphere and water column, prior to detection.

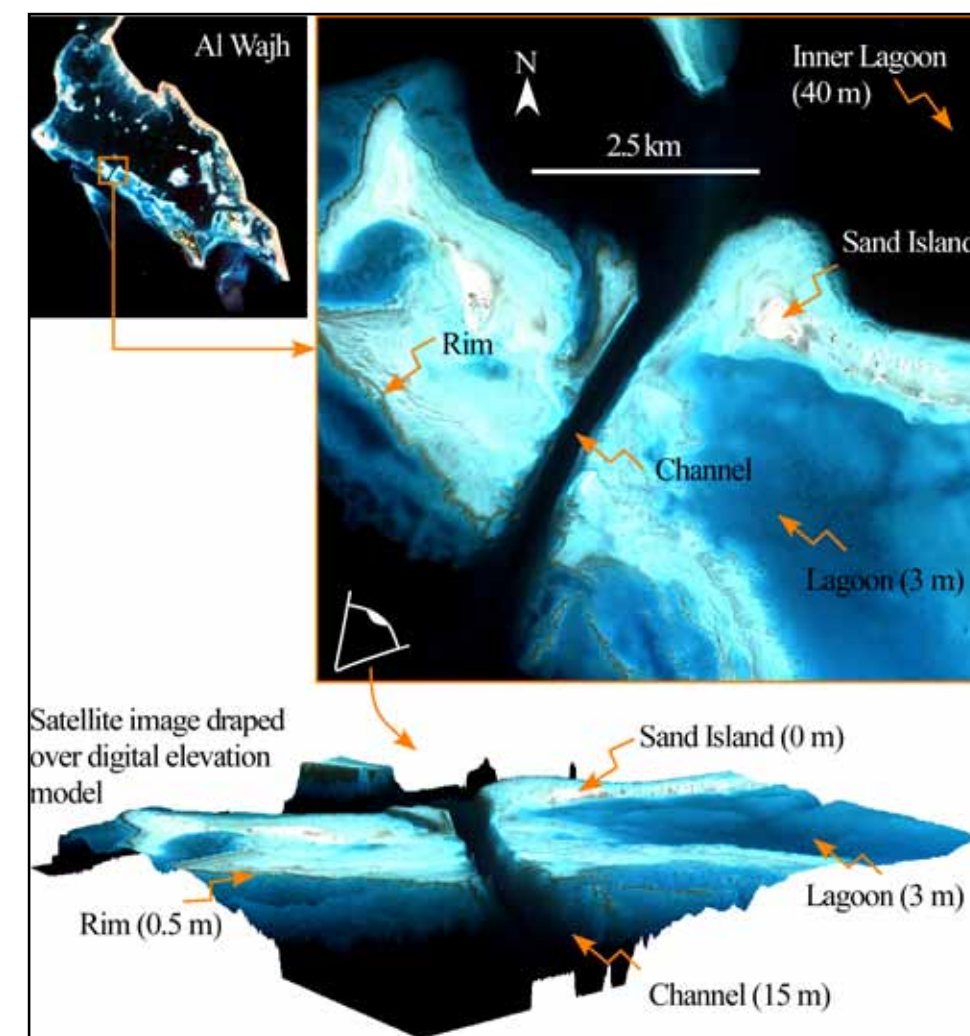
## Preprocessing

At the sensor, measures of the quality and quantity of light reflected from Earth’s surface are stored as a digital number on a per-pixel basis. This light is partitioned into one of several spectral bands that are first converted to “real-world” units of radiance, a parameter that describes a flux of electromagnetic energy. Using mathematical models that account for absorption and scattering of photons in the atmosphere, this conversion yielded pixel values in units of remote sensing reflectance (%). Because direct measures of atmospheric quality were not available at the time of image capture, model atmospheres typical to the tropical maritime climate of Saudi Arabia were used during processing. Nevertheless, some images were still compromised by mild sea-surface-glint, consisting of small bright portions on the image where light reflecting off of the water surface, overwhelming and obscuring the signal emanating from the seabed. Glinted pixels in an image were corrected using models based on their comparative brightness in the near-infrared (NIR) portion of the visible spectrum, on a scene-by-scene basis, depending on the degree of sea-surface-glint.

## Optically derived water depth

Using multispectral or hyperspectral imagery and the relevant subset from the millions of acoustic depth soundings collected, seafloor topography was optically derived. Topography relates to changes in shape and elevation across a lateral surface. Digital representations of seascape topography are termed digital elevation models (DEMs). The most accurate DEMs derived from optical remote sensing imagery have a meter-scale lateral resolution and vertical accuracy of several tens of centimeters to water depths up to 25 meters. As previously discussed, light is absorbed and scattered as it moves through the water column, a process termed “attenuation.” Levels of attenuation depend upon the turbidity of the water, as well as the wavelength of light considered. Light is attenuated approximately exponentially with depth in the water column with respect to increasing wavelength. Depth-retrieval algorithms that rely on a single wavelength of light are ineffective in the common case where the seabed is comprised of multiple habitats with different spectral reflectance. The reason for the failure is that two (or more) factors are influencing the spectral signature received by the remote sensor, namely substrate type and water depth. An enhanced result can, however, be achieved using the

ratio between two spectral bands. The band-ratio method capitalizes on the fact that short wavelength light (blue) is attenuated less rapidly than longer wavelength light (green). As different wavelength bands are absorbed by water disproportionately, their between-band pixel values will differ. The band with the greatest absorption will always therefore yield lower values. With increasing depth the reflectance of both bands decreases, however, the reflectance of the band with the highest absorption (green) decreases proportionately faster than the lower absorption (blue) band. With increasing depth, the ratio of blue to green light for a point on the seabed will increase. The band-ratio method also compensates for variability in the character of the seafloor. The changing reflectivity of substrates on the seabed affects both bands similarly. Changes in depth, however, affect the high absorption (green) band to a greater degree. The change in ratio due to depth is much greater than that caused by any change in substrate reflectivity, and different bottom types at the same depth will therefore have the same spectral ratio.



QuickBird multispectral satellite imagery for Al Wajh bank. Top left: the entire area. Top right: a closeup of the reef structure and channel. Bottom: Digital elevation model (DEM) derived from optical remote sensing imagery for the same area.

## Calculating water depth

A mathematical model was employed that involves taking the ratio between the log of the electromagnetic energy measured in the blue satellite waveband, with the log of the neighboring green band. The output is an image containing values that vary strongly based on differing water depth, but only weakly as a function of seabed character. This “pseudo-bathymetric” image is subsequently calibrated to real-world depth with reference to the large number of acoustic soundings obtained in the field. The resultant DEM yields a calibrated and robust bathymetry to the maximum depth of green light penetration (i.e., the shorter of the two wavelengths used in the band-ratio), which typically is on the order of 15-25 m water depth. Accuracy is generally within  $\pm 50$  cm at depths below 5 meters, increasing to  $\pm 1.5$  m at 20 meters. DEMs calibrated by acoustic data provide a good approximation of surface topography across all the areas mapped in the Atlas. DEMs may be used to further refine imagery for spectral classification of habitats through the process of water column correction. The addition of seabed topography further allows a fully three-dimensional reconstruction of the depositional environment. Seabed morphology can be used to reconstruct processes sculpting the system across geological and ecological time-scales.

## Water column correction

The spectral influence of the intervening water column may hamper seafloor habitat classification from optical sensors, requiring use of a correction algorithm that empirically accounts for the near-exponential attenuation of light by water with increasing wavelength. The optical quality of seawater is highly variable. Spectral profiles of light attenuation were collected in the field using a submersible spectroradiometer to allow the selection of viable water-quality parameters for model-input. The thickness (depth) of the water column was known based on from-image depth derivation calibrated by acoustic soundings. Spectral profiles extracted from the imagery over homogenous areas of seafloor substrate provided the means to validate the water-column correction model. Following depth correction, spectral-based classification can return a much more accurate habitat classification product than would be delivered if the attenuation of light by water was ignored. To neglect this processing step would lead to the undesirable situation whereby depth contours, rather than the true distribution of a seabed habitat, would be mapped.

## Image masking

To maximize the efficiency of spectral classification algorithms, all areas irrelevant to the mapping algorithm were masked, including areas of land, cloud, and shadow, and optically deep water (e.g., depths below the easily detectable reflective return from the seabed). Infrared light is

fully absorbed within the first few centimeters of the water surface. Land and cloud pixels were easily separated from water-covered pixels using the significantly higher reflection in this region of the electromagnetic spectrum. In the case of the occurrence of clouds, a mask was repositioned to also eliminate areas of the sea-surface darkened by cloud-shadows. Shaded imagery may still contain spectral information relevant to habitat classification but must be treated separately, as comparable substrates in such areas will have very different reflectance values. Optically deep water was identified within the imagery by thresholding low values within the previously described two-band log-ratio image used for depth-derivation. By examining image-values across an area of sand-dominated and sloping seabed, it is possible to set a threshold at which there ceases to be any increase in band-ratio with increasing depth. This value was taken to represent the onset of optically deep water. Beyond this point, spectral-based classification is no longer feasible, and acoustic methods must be relied upon to interrogate seabed structure.

## Hyperspectral image processing

Most of the processing tools used for multispectral imagery were easily transferred to the acquired hyperspectral data. Because of the larger number of spectral bands available when using a hyperspectral sensor, it is theoretically possible to discriminate a greater number of optically similar seafloor types, such as the separation of live from dead coral, even within a single pixel (a process termed spectral-unmixing). Most modern hyperspectral sensors, such as the AISA *Eagle*, collect hundreds versus tens of spectral bands. Because spectral differences between individual seafloor components may be very subtle in magnitude, as well as being positioned within narrow regions of the visible spectrum, much of the data a hyperspectral sensor collects may be superfluous to a given application. An efficient approach therefore entails identifying the optimum bands for differentiating habitat classes, and then tuning the airborne sensor to pool its resources into these areas of the electromagnetic spectrum.

## Thematic habitat maps

Thematic habitat maps represent the bulk of the maps in this Atlas. Producing such maps from remotely sensed imagery involves assigning image pixels to thematic habitat classes. Unlike a spectral-unmixing classification, each considered pixel in the image must be categorized as one, and only one, habitat class. As a first step in the thematic habitat mapping process, a classification scheme was developed. A number of different techniques were then hybridized to create the most accurate map possible from the image and ground-truth data acquired. Spectral, textural, edge-detection, as well as landscape context, were all considered within the classification workflow.

## Image classification

### Edge-detection

Edge-detection is a process whereby boundaries are identified within an image corresponding to where brightness changes sharply across a narrow spatial threshold. Edge-detection was used principally to quickly identify objects with clearly defined (i.e., crisp) boundaries. This freed up processing time for defining more complex gradated habitat boundaries. Under ideal conditions, the application of an edge-detecting algorithm would result in a set of polygons corresponding to boundaries between habitats. Within images of underwater habitats, this ideal is rarely attainable; however, as many spectral discontinuities may arise due to differences in depth, orientation, illumination, as well as changes in the physical makeup of the seafloor. Crisp boundaries between land-cover types are uncommon in nature. This study therefore did not rely on edge-detection alone for mapping. The technique was used as an efficient way to delineating boundaries between spectrally very bright versus dark habitats, such as exist between sand and seagrass.

### Spectral classification

Different substrates vary in the amount of light they absorb (and reflect) at different electromagnetic wavelengths. Building on this fact, spectral classification algorithms are common and powerful tools in optical remote sensing. Such mathematical models use from-image statistics of reflectance to train probability-driven classifiers. Training classes, comprising groups of pixels with similar spectral character, were taken from homogeneous areas representative of a given habitat as defined by tethered-video observations. Training classes were split based on habitat and depth to avoid the inadvertent classification of depth thresholds that may remain in areas where water-column correction has not been completely successful. Training classes are commonly referred to as regions of interest (ROIs). Prior to running a classification, the reflectance spectra described by the different ROIs were explored within bispectral plots, which depict the pixel values of one spectral band plotted against another. In the ideal situation, points within these plots would cluster tightly together as a function of seabed type, with little-to-no overlap between different classes. Where overlap occurred, however, this was taken as a strong indication that additional classification tools, such as edge-detection and textural analysis, were necessary. A maximum likelihood classification algorithm was used to calculate the probability that a given pixel belonged to a specific class. The algorithm was not applied to areas that had already been masked as containing terrestrial, deep-water, or cloud-contaminated pixels. Each pixel was assigned to the class with the highest probability value output by the maximum likelihood algorithm. Classified pixels relating to the same habitat, but at different depths, were joined in a subsequent editing step.

## Textural analysis

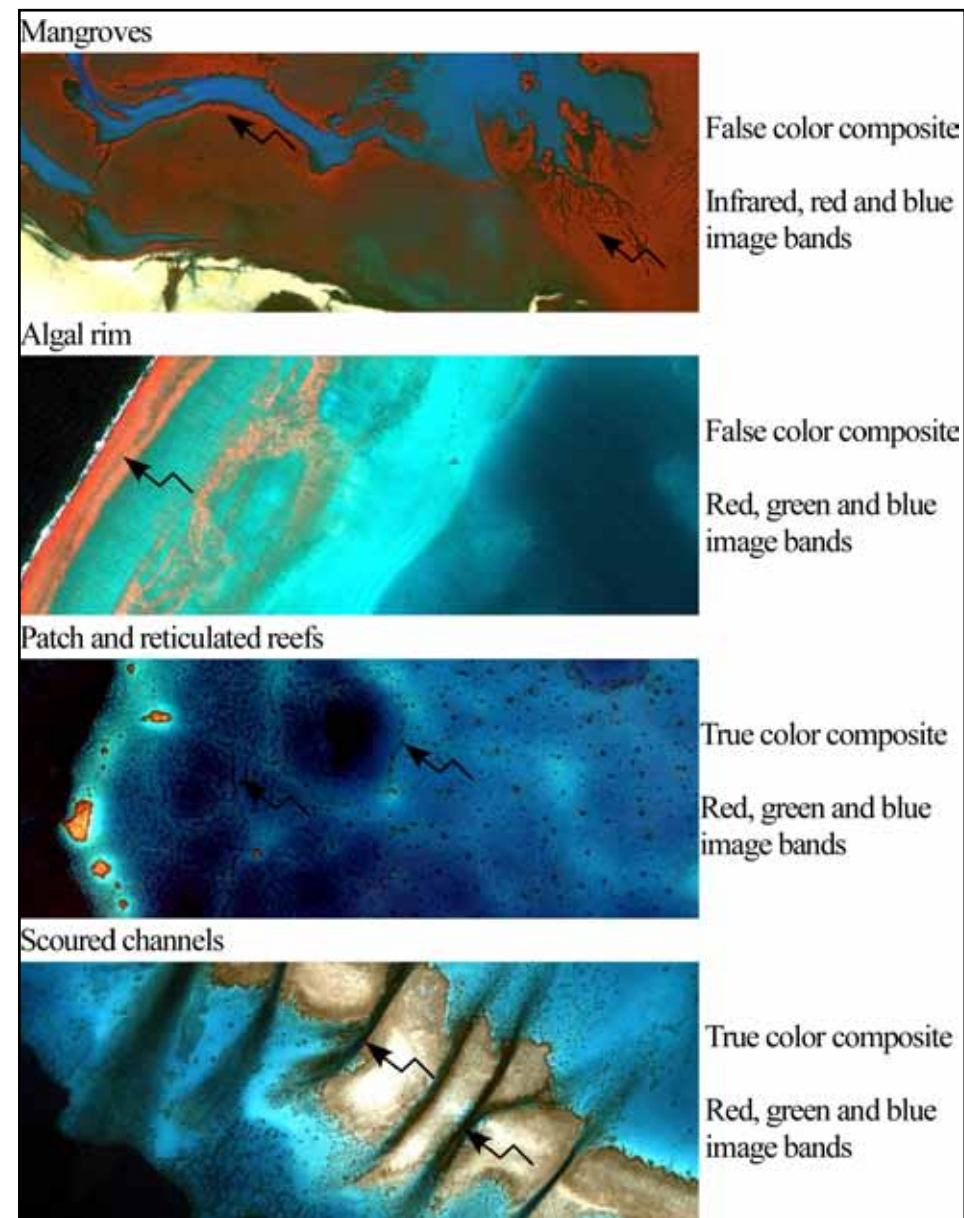
Probability-driven approaches will by definition fail when the desired habitat classes are spectrally inseparable within the remote sensing imagery. Under such a scenario, textural tools were put to good effect. Texture-based classification considers the systematic variation of brightness within a square of numerous image pixels, termed a “kernel.” Within the kernel, the brightness values recorded by the sensor may be regular and auto-correlated, or else disparate and random. As for the spectral component of the imagery, this textural property varies as a function of seabed type. Through processing with a textural-extraction algorithm, an additional “textural” image can be produced from the original spectral data. This can be classified in a similar way to the optical scenes. Unlike spectral classification that considers multiple image-bands, however, the textural extraction is conducted on a single band for which we employed the blue band, because it confers the greatest penetration into the water column.

## Contextual editing

Landscape contextual editing draws on the fact that geomorphological and ecological zonation across a depositional system follows generic and logical rules (near-shore sediments, for example, are not encountered on the reef-edge). Decision rules based on such cross-platform occurrence of habitat may therefore be imposed to guide habitat classification. The image was segmented into zones based on reef geomorphology (for example, near-shore, lagoon, back-reef, reef crest, and reef-slope). A small degree of habitat misclassification is unfortunately inevitable even when both spectral and textural classifiers are employed. Contextual editing provides an efficient means for addressing such errors, placing pixels into classes appropriate to the zone in which they are located. Often a habitat class would transcend multiple zones. Seagrass, for example, was never found on reef crests but is found in both the lagoon and near-shore. Under the scheme devised, a pixel therefore could not be classified as seagrass within the reef crest zone but would be permissible within the lagoon and near-shore. Similarly, fine-grained sediment, such as mud, does not accumulate in high-energy zones such as the fore-reef and shallow slope; and a decision-rule based on this partitioning can be defined. Use of DEMs provides further contextual support. Sediments, for example, tend to accumulate at the base of slopes and in troughs in the topography of the landscape, while being absent on topographic highs.

## Filtering

Misclassification due to localized aberrations in the remote-sensed image (such as might result from a poorly corrected sea-surface-glinted pixel), must be guarded against. To this end, filters were used. A filter window refers to the number of pixels surrounding a focal pixel over which the filter operates. A convolution filter was most commonly used.



**False and true color composite images created using three of the four QuickBird satellite image bands (infrared, red, green, and blue). Band set used to create each image plate is indicated to the right. Different features (black arrow), such as mangroves, algal rims, patch and reticulate reefs, and scoured channels, can be easily visualized based on their spectral response in different image bands. Examples are taken from the Al Wajh reef system.**

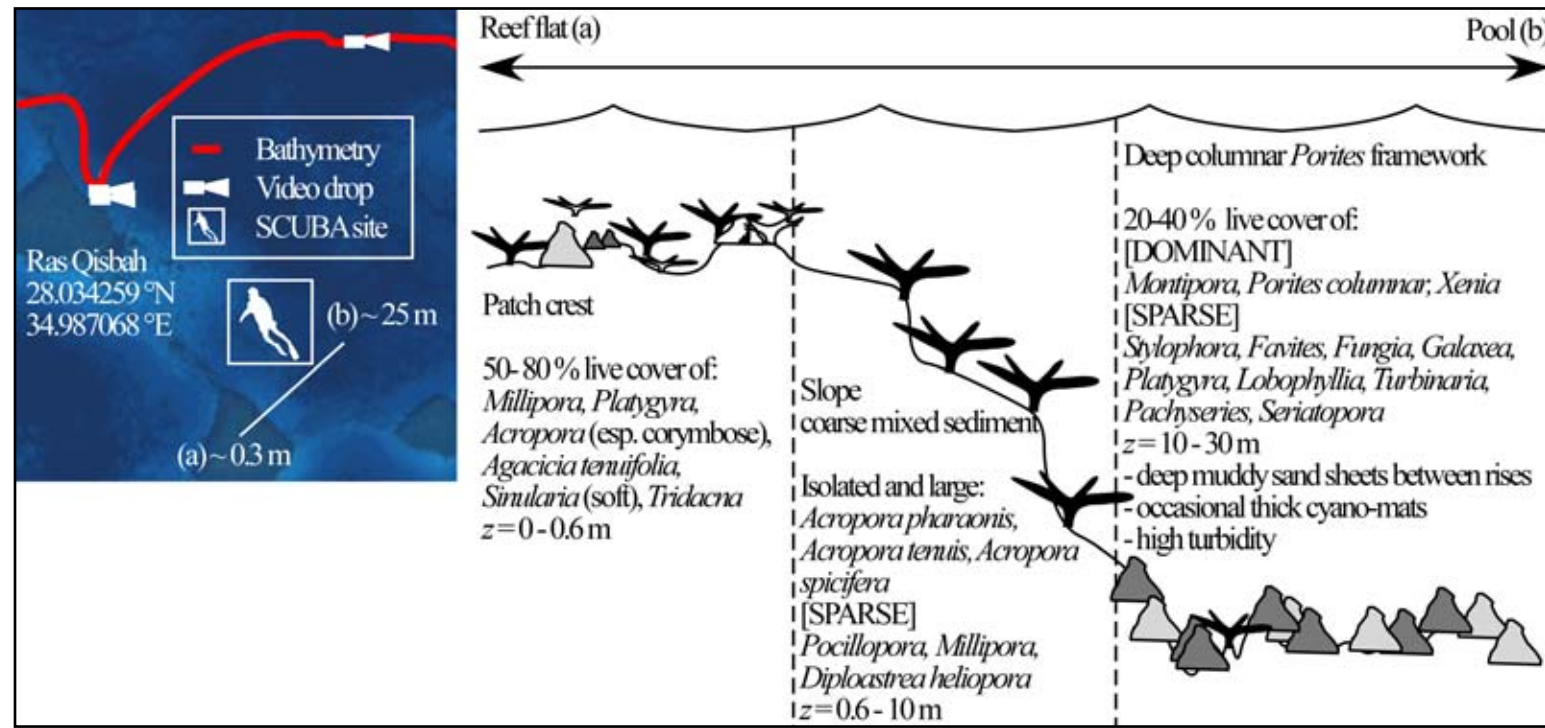
This class of filter produces an output where the value of the focal pixel is a function of the weighted average of the surrounding pixels. In natural systems, areas of the same habitat tend to be clumped. If a number of neighboring pixels was similarly classified, it is therefore probable that a focal pixel was correctly classified. A median filter was used to achieve this result. This is a type of convolution filter, which is particularly adept at removing the “salt and pepper noise” or “speckle” that arises in a noisy classification. The median filter replaced outlier pixel values in the habitat classification result, yet preserved any habitat patch-edges that were larger than the dimensions of the filter window. Typically a 3 x 3 median filter was used, whereby the pixel in the center of the window was replaced by the most prevalent value of the eight surrounding pixels (i.e., the median value).

## Quality control

As a final step in the habitat classification process, map products were subjected to visual quality control, answering the broad question: Did habitat demarcation follow identifiable patterns in the imagery? Where the answer to this question was clearly “no,” a second iteration of the classification process focusing specifically on the area of concern was carried out. To conduct this procedure, contrast enhancements were used to visualize different features within the spectral imagery at different water depths. A remote-sensed image scene often contains substrates that are spectrally very different, such as land and water. Most remote sensing software will apply a default linear contrast stretch across the whole of the loaded scene, thereby hiding from view most submerged features. By focusing a contrast stretch on a specific portion of a scene with a narrow range of pixel brightness, features that have similar but still subtly different in their reflectance characteristics were more fully exposed. The habitat classification was compared to imagery under a number of different contrast enhancements.

## Accuracy assessment

An accuracy assessment was carried out using a selection of ground-truth data that had purposely not been used to support the classification workflow. A classification error matrix (also known as a confusion matrix or contingency table) was used to quantify map error. Map pixels in the thematic classes were compared to ground-truth data. Overall accuracy, errors of omission (producer’s accuracy) and commission (user’s accuracy) were calculated for each class. Producer’s accuracy is a percentage measure of how often a particular ground class was correctly classified, calculated by dividing the total number of correct pixels for a ground class by the total number of ground truth pixels for that class. User’s accuracy refers to the percentage of a map class corresponding to the correct ground class. User’s accuracy is calculated by dividing the number of correct pixels for a map class by the total pixels assigned to that class.



Example of a reef profile generated from broad-scale scuba assessments, drop-camera imagery and bathymetry. The site location, depth profile, species composition, and relevant geomorphological information are shown.

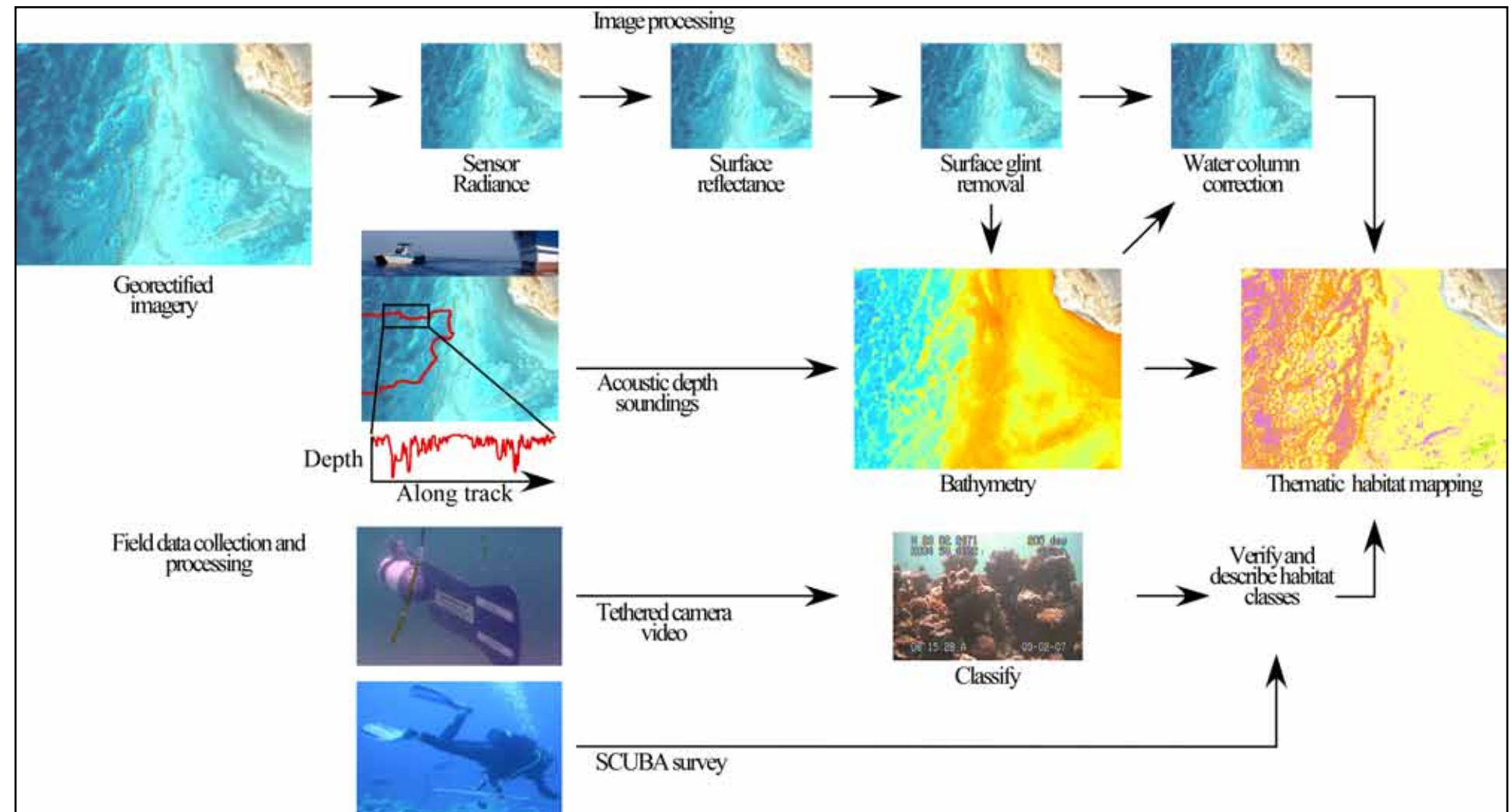
## Data conversion

Habitat classifications were converted to GIS-ready, vector-based map products using remote sensing and GIS software. Pixel-based products, termed “rasters,” were converted into vector-based data. Under this system of storage, clumps of adjacent pixels that comprise a single patch of habitat are grouped as a single vector shape or polygon. Because only information relating to the boundary coordinates of the polygon is stored, such data is less intensive and easier to use for a number of applications. So called “shape files” are easily integrated with Web-based geographic media for distribution to the masses. Attributes may be subsequently appended to a habitat polygon. Aside from a description of the relevant habitat class, such attributes might include geometric measures, for example area or perimeter of the habitat patch; measures of environmental context, such as distance from shore or distance from an urban center; measures of human use, for instance fishing pressure across the habitat patch or recreational scuba; or localized environmental data, including meteorological measurements, water depth across the polygon, water temperature, or results from fine-resolution seafloor survey. In short, anything that can be measured and appended with a spatial coordinate can be brought into a GIS. As a GIS-ready product, the marine habitat data presented in this Atlas are primed for more in-depth exploration.

## A GIS-ready map product

A geographic information system (GIS) is a software application for capturing, displaying, storing, managing, and analyzing digital geospatial data. Perhaps most simply, GIS can be thought of as the marriage between mapping and database technologies. The coastal environment is not simply the collective of marine habitats presented in this Atlas. Coastal systems are also the venue for many layers of human use: fisheries, tourism, mineral and oil extraction, commercial sea traffic, to name but a few. Based on observations from around the world, it is recognized that terrestrial processes, both human and natural, affect coastal and offshore systems. Sediments and pollution from inland runoff, along with increased nutrient loads, are being delivered to oceans. Because GIS supports both a data storage and data exploration, information from such seemingly disparate sources can be brought together and analyzed within their true spatial context. A GIS-ready habitat map represents the precursor to a more synoptic view of the marine system. It allows for more enhanced ecological investigation, as well as improved marine spatial planning and management.

**Bottom right:** Work flow for deriving water depth and producing benthic reef habitat maps. QuickBird satellite imagery is prepared for analysis through a series of processing steps, yielding images of high radiometric quality and consistency. Field data provide ground control to facilitate the training of mathematical algorithms.



# Major Biotopes of the Red Sea Coastline

The Red Sea coastline varies geomorphologically from a rugged coastline with marine terraces and rocky shores, to coastal sabkhas, alluvial plains, and wadis—often up to 30 km in width. There are a large number of dry riverbeds, alluvial fans, and estuaries extending along the coast. Extensive salt marsh communities and mangrove thickets occur in several locations, while sandy and muddy beaches are found in other areas. Coastal environments include open-shelf basins; fringing, barrier, and patch reefs; and lagoonal habitats. In addition to coral reef biotopes, shallow marine environments contain seagrass beds, algal flats and algal reefs, and sand/mud biotopes that may be colonized by cyanobacteria or algae.



A fringing reef located in the Farasan Islands. The reef begins close to shore, lacks a prominent reef flat and lagoon, and drops quickly into deep water.

## Coral reefs

The Saudi Arabian Red Sea coast includes most of the world's major reef types, including mainland fringing reefs, island fringing reefs, platform patch reefs, "pinnacles" and barrier reefs, as well as reef types restricted to the Red Sea, namely ridge reefs (Guilcher 1988). Reefs are also often developed in sharms along the mainland coast, a characteristic reef-form restricted to the Red Sea. While most reefs are actively accreting, levels of reef development vary widely. For example, there are subsurface patch reefs with no reef flat, narrow "contour" fringing reefs with reef flats <30 m wide, large platform and barrier reefs with reef flats often >100 m wide, and tower reefs reminiscent of atolls. The central-northern area extending from north of Jeddah to Haql in the Gulf of Aqaba supports a near-continuous coral reef tract composed of mainland and island fringing reefs, various forms of patch reefs, coral pinnacles and "ribbon" barrier reefs (Ormond et al. 1984). Within this area, the most extensive mainland

fringing reefs are found around Rabigh, Ras Baridi, UmLuj, Al Wajh, and in the Gulf of Aqaba. Island fringing reefs are also common in the Tiran area and from Al Wajh Bank to UmLuj. Circular and elongate patch reefs are widespread in offshore waters (< 50 m depth). Some patch reefs are associated with sand-coral islands, while others are submerged (Riegl and Piller 1997). Both forms are common in the Al Wajh Bank and south from UmLuj to Rabigh. "Reticulate" patch reefs, also known as "labyrinths and mazes," (Ormond et al. 1984) are composed of interconnected networks of reef matrix separated by sand, forming intricate reticulate patterns. These are particularly well developed in shallow waters (< 10 m depth) near Tiran and southern Al Wajh Bank.



Shallow reef communities around a small island in the Farasan Banks.



Networks of patch reefs off a small island within the Farasan Islands.

Pinnacles (also known as coral "bommies" surrounded by sand) are also found in shallow water (< 10 m depth) in the Al Wajh Bank and Tiran areas (DeVantier et al. 2000). Barrier reefs composed of platform and "ribbon" reef structures are located further offshore, especially on the edge of the "continental" slope, where water depths increase from < 50 m to > 200 m. The best-developed barrier reef system is found along the seaward margin of the Al Wajh Bank, where it forms a continuous line of reefs stretching for nearly 100 km and separated by narrow (< 200 m width) channels (Ormond et al. 1984, DeVantier et al. 2000). The "Little Barrier Reef" found further south near Yanbu is also a barrier reef system, but it has a different gross geomorphological structure (Ormond et al. 1984, Sheppard and Sheppard 1985). The central-northern Saudi Arabian Red Sea does not support atoll-like or "tower" reefs; these are more characteristic of southern areas and the outer Farasan Bank (Ormond et al. 1984).

To the south of Jeddah, reefs become less common along the mainland coast, primarily due to differences in topographic features, and higher sediment loads and turbidity (Price et al. 1998). Complex reef structures do occur, however, further offshore in the Farasan Banks and Farasan Islands (Ormond et al. 1984). These include tower reefs, which are similar in gross geomorphology to atolls and ridge reefs (Guilcher 1988), which are longitudinal ridges lying along the axis of the Red Sea. Ridge reefs are thought to be formed from a combination of normal faulting from the progressive opening of the Red Sea and the underlying slat deposits moving upward. Both of these are rare or absent in other areas of the Saudi Arabian Red Sea.



A tower reef with a characteristic atoll-like structure within the Farasan Banks. A wide reef flat forms a rim, separating the outer reef slope from the central lagoon.

## Seagrass beds

Twelve species of seagrasses, belonging to seven genera, are found in the Red Sea (El Shaffai 2011). The northern Red Sea (north of 25°) has up to eight species, while the central Red Sea (18-25° N) has the highest diversity (Jones et al. 1987). These flowering perennials tend to grow on sandy or muddy bottoms, usually between 2.5 and 10 m. depth, primarily in sheltered areas. A few species are also found on the reef. Seagrass cover and biomass are affected by light levels, a function of depth and turbidity, as well as substratum type, water movement, temperature, and salinity. The distribution of seagrass beds progressively increases in abundance to the south, largely due to the presence of a wider and shallower shelf, a higher proportion of unconsolidated sediments, and less extreme temperatures and salinities. Individual species also exhibit preferences to certain depths and sediment types. For example, *Thalassodendron ciliatum* and *Thalassia hemprichii* inhabit coarser sediments, while *Enhalus acoroides* is found in soft muds (Price et al. 1988). Three species of *Halophila* (*H. stipulacea*, *H. ovata* and *H. ovalis*) are known to occur to depths of 70 m and 30 m respectively (Hulings and Kirkman 1982; El Shaffai 2011), while *Halodule uninervis* is found in both intertidal and shallow subtidal habitats. Several species (*T. hemprichii*, *Thalassodendron ciliatum*, *H. ovalis* and *H. uninervis*) can form dense monospecific assemblages, while mixed assemblages (*T. hemprichii*, *Cymodocea rotundata*, *Syringodium isoetifolium* and *H. stipulacea*) also occur.



A medium density *Thalassia* seagrass meadow at 6 m depth in Ras Al-Qasabah.



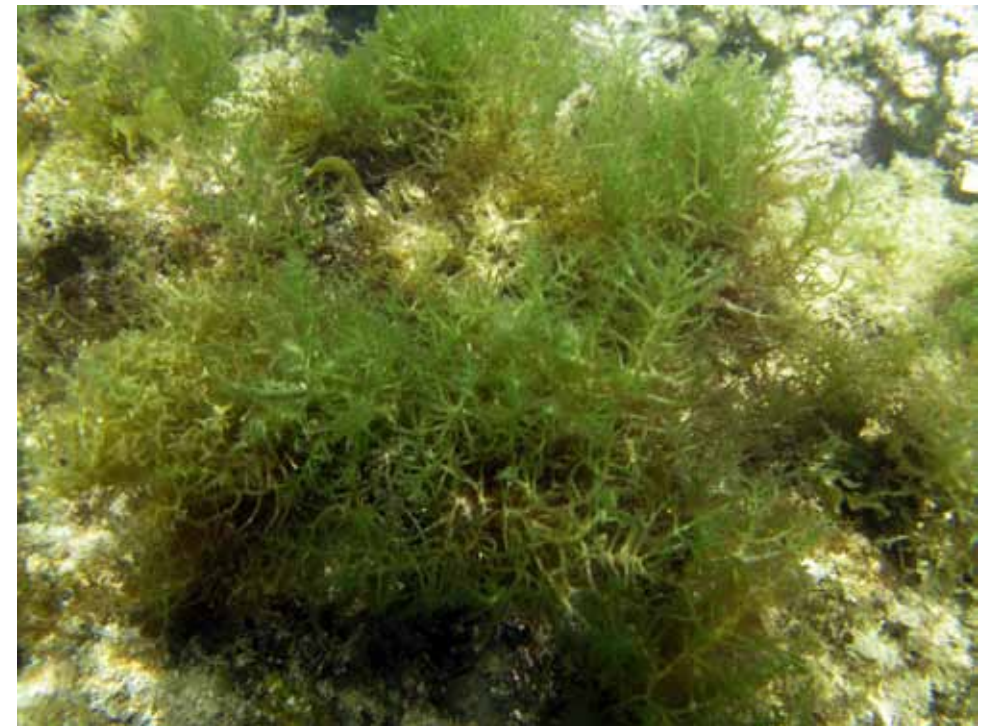
Closeup of the delicate *Halophila ovalis* seagrass in Al Wajh Lagoon, 6 m. depth.



Green calcareous macroalgae (*Halimeda* sp.) on a sand flat within the lagoon in Al Wajh, 5 m depth.

## Algal mats and Algal reefs

Extensive areas dominated by macroalgae occur on reefs and other hard substrates and also in certain subtidal soft-bottom habitats. Algal communities in the Red Sea are highly diverse, consisting of over 500 described species and many new species. In the northern and central Red Sea algal lawns consist primarily of filamentous green algae and small brown algal species, while large brown algae (eg., *Sargassum* and *Turbinaria* spp.) dominate shallow reef flat communities in the southern Red Sea. While standing stock generally tends to be low, with a high turnover as a result of intense grazing pressure, productivity is high. Most algal communities show a strong seasonality, with a direct correlation to water temperatures; fronds of many species tend to be annual, although stipes and holdfasts may remain attached to the substrate for many years. Algal cover on hard substrates drops precipitously from 50-90% to <5% cover at depths greater than 5 m. However, much higher cover can occur in reefal habitats that have experienced recent disturbances and in areas with low herbivory and high nutrient input. Soft-bottom subtidal communities can also contain rich biological assemblages with high productivity, due to the presence of diatoms, mats of cyanobacteria and filamentous algae. In some areas, calcareous and encrusting red algae may also become abundant, forming rudimentary spurs where wave energy is adequate for their development. Under low-energy conditions in the Farasan Islands, algal reefs may be built by calcareous algae, forming on top of coarse sand in 2-4 m depth. These develop steep sides and often extend up to the low tide level.



A macroalgal community on a reef flat in the Farasan Islands, 1 m depth.

## Mangroves

Mangroves are found throughout the Red Sea, occurring mainly in sheltered areas behind reef flats, in bays or creeks, and on the leeward side of offshore islands. In most locations, mangroves grow as relatively thin forests along the shoreline on near and offshore islands and at the margins of fringing tidal creeks and channels of various size. The largest concentrations of mangroves are found in inner protected lagoons and sheltered embayments where water depths range from 0.5-1.5 m, especially in the south. Mangroves are also often associated with seaward terminations of wadis.

Mangroves form two distinct assemblages, one occurring in soft bottom habitats and a second, found primarily in the northern Red Sea, in hard-bottom habitats behind reef flats. The latter, often referred to as “reef mangals” (Por et al. 1977) grow as a thin veneer overlaying uplifted rock or fossil reefs, with stunted trees anchoring in small sediment filled cracks and crevices. Mangrove development increases toward the south, coinciding with the gradual disappearance of stony corals in nearshore habitats and a shift to offshore locations, a wider continental shelf, warmer temperatures, increased availability of muddier substrate, higher nutrients, and more freshwater. These stands can be 100-500 m wide, with trees that range in height from 5-7 m.

In general, mangrove distribution is patchy north of Al Lith (Farasan Banks), with the largest and best developed stands found near Sharm Zubeir, on the shoreline between Al Wajh and UmLuj, Al Wajh Bank, near Yanbu, between Rayyis and Mastura, Rabigh area, south of Jeddah, and Qishran Bay. Mangroves are more dense to the south of Al Lith, fringing most of the shoreline and forming a semicontinuous belt. The largest and most dense stands in the south have been found at Khor Abu Saba, Midaya, Besari (Mandura et al. 1987), Al-Quham, Khor Itwad, Shi’b-al-Kabir, and Khor Al-Ja’afirah (Price et al. 1987).

There are four species of mangroves reported to occur historically along the Saudi Arabian Red Sea coastline: *Avicennia marina*, *Rhizophora mucronata*, *Bruguiera gymnorhiza*, and *Ceriops tagal*. *Avicennia marina* is by far the most common species, flourishing in extreme environments. It survives high salinities (40-50 ppt) and extreme water temperatures (12-40° C). The northerly limit for distribution of *A. marina* is along the Sinai Peninsula near Sharm Zubeir (27° 25’N), with a southern range beyond the Farasan Islands and into Yemen. *Rhizophora mucronata*, which is much less widespread, typically coexists with *A. marina* in 11 locations (Al-Wetaid 2003). The most extensive *R. mucronata* stands are found in the Farasan Islands and Al Wajh Bank.



Extensive mangrove communities are found in embayments within the Farasan Islands.



*Avicennia marina* mangroves inhabit the leeward side of offshore islands in Al Wajh Bank.

## Habitat Classification Scheme

For purposes of this Atlas, a “habitat” was defined as “a unique combination of gross topographic structure, biotic community, sediment/hardground composition occurring consistently across at least the scale of an image pixel (2.4 m<sup>2</sup>).” Considering the geographic scope of this study, the classification scheme had to be both coarse enough to facilitate rapid mapping, yet detailed enough to capture the range of habitats encountered throughout the length of the Red Sea. Habitat mapping is carried out using optical remote sensing. The habitat classes therefore also reflect what is physically possible to discriminate from an image. The classification scheme was developed primarily in the Farasan Islands and Ras Al-Qasabah regions. These represent the northern and southern most extents of mapping effort. The mapping scheme held true for the other areas mapped with little need for adjustment. Tethered-video footage was reviewed from the Farasan Islands and Ras Al-Qasabah, and categorized based on variation in topography, the composition and abundance of the biotic community, as well as the distribution of sediment or Hardbottom. Field notes and fine-scale photography from scuba surveys were used to verify and adjust this categorization where necessary. Where image classification tools could not distinguish between habitats, these habitats were merged. For example, it was not possible to reliably differentiate between high-density seagrass beds (50-100% cover) and medium-density seagrass beds (15-50% cover), the two classes were therefore merged to form the “seagrass meadows” class (15–100% cover). Sparse seagrass (0-15% cover), due to its high sediment content, could not be separated from the sand class, and was therefore merged into shallow sand sheets or deep lagoonal sand classes. The final habitat classification scheme comprised fifteen different classes as follows:

- 1) windward coral crests;
- 2) leeward coral crests;
- 3) dense *Acropora* thickets;
- 4) columnar frameworks;
- 5) reef walls and drop-offs;
- 6) sparse corals, rubble and sand;
- 7) seagrass meadows;
- 8) macroalgae and sponges on hardgrounds;
- 9) cyanobacteria mats on sand;
- 10) mangroves and nearshore vegetation;
- 11) scoured channels;
- 12) carbonate hardground and reef flats;
- 13) shallow sand sheets;
- 14) deep lagoonal sands;
- 15) sand and mud flats.



# Habitat Classes

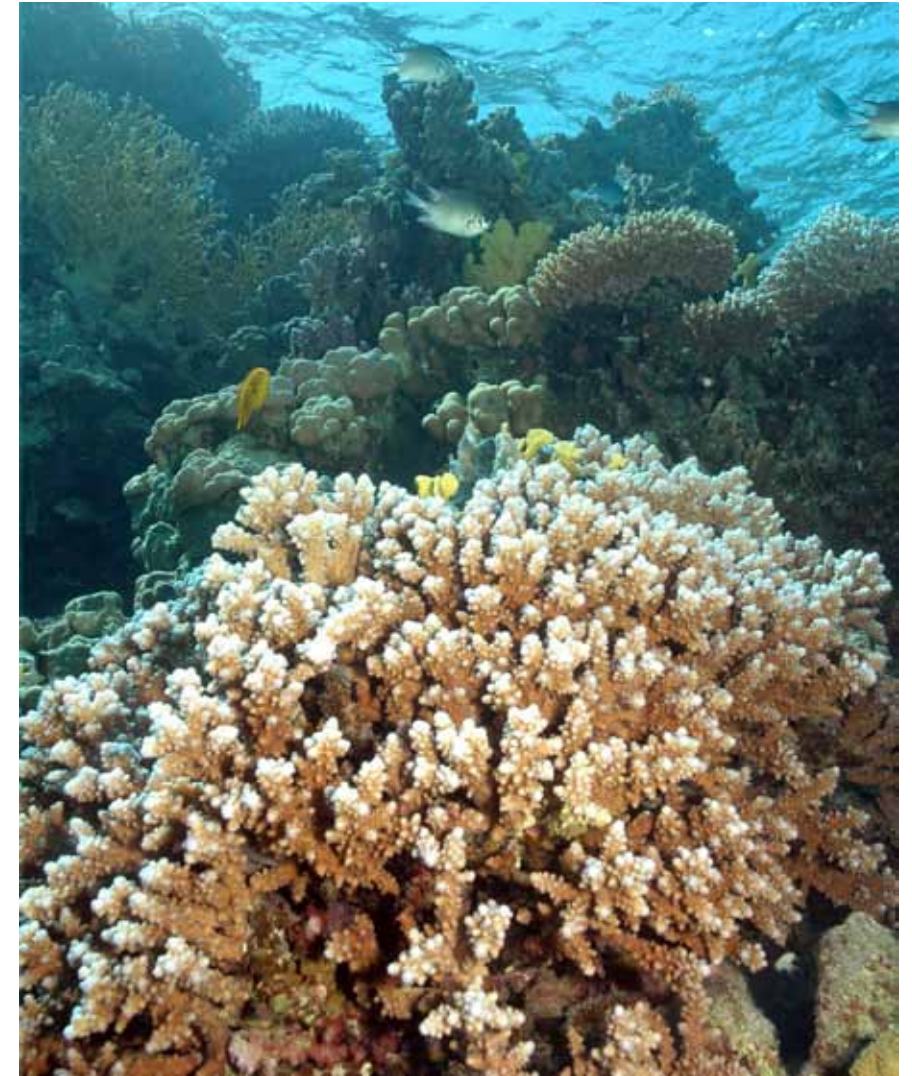
Habitat maps created for the Red Sea coast of Saudi Arabia extend from the shoreline, at mean low water, to about 20-30 m depth. Habitats extend from the mainland up to 100 km from the coastline and include reef and associated communities that fringe offshore islands, as well as submerged reef and hardground habitats. Both biological cover types and geomorphological structural types were merged to define the specific habitat. A “habitat” was defined as “a unique combination of gross topographic structure, biotic community, and sediment/hardground composition occurring consistently across the scale of at least an image pixel (2.4 m<sup>2</sup>).”

## Windward coral crests

Windward coral crests are diverse, high-energy assemblages dominated by hermatypic corals built upon columnar and massive *Porites* frameworks. Located immediately seaward of the reef flat community; includes the fore reef slope habitats, ridges, and reef terraces. Corals tend to be low-relief massive species interspersed with branching, plating, and columnar species that have short, stout branches or columns including species of *Acropora*, *Pocillopora*, *Stylophora*, and *Favia*. Other corals, including *Favites*, *Seriatopora* and *Fungia* may also occur. Live coral cover is typically high (50-80%) and macroalgae is rare. Typical depth: 1-5 m.



Windward reef slope, Farasan Banks, 4 m depth.



Leeward reef slope, Al Wajh Bank, 3 m depth.



*Acropora* dominated reef terrace at 3 m depth, Farasan Banks.

## Leeward coral crests

Leeward coral crests are characterized by rich, hermatypic coral cover dominated by small *Acropora* spp. colonies, also species of *Porites*, *Favia*, *Favites*, and *Seriatopora hystrix*. Live coral cover is typically 50-80%. The most diverse crests are found on shallow lagoonal fringes. On certain southern reefs (Farasan Banks and Islands), macroalgae may be more abundant and intermixed with coral, with a dominance of stout brown algae including *Sargassum* and *Turbinaria*; these algae taxa generally form dense assemblages on the adjacent reef flat, especially on nearshore reefs. Typical depth: 1-5 m.



Diverse coral community, leeward reef, Farasan Banks, 5 m depth.

Windward reef slope near the drop-off, Yanbu Barrier Reef, 5 m depth.

## Columnar frameworks

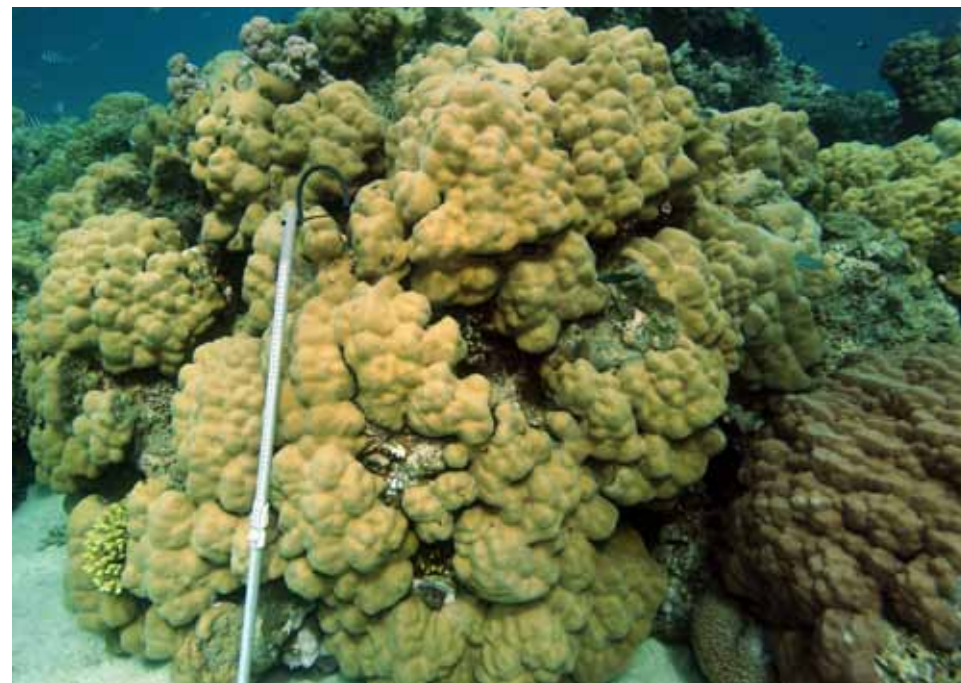
Columnar frameworks are topographically complex habitats constructed of high-relief columnar *Porites* colonies. Live coral cover is low, generally less than 15%, although there can be areas with large lobate colonies of *Porites* that are still largely alive. Columns are often partially colonized by small corals, including numerous plating, encrusting, and submassive growth forms. Columnar structure becomes shorter and broader with increasing depth. Depressions in the framework are sediment-filled with deeper areas characterized by fine-grained to muddy sediment sheets. Antecedent morphology could be karstic, but the sediment-filled depressions also suggest that the landscape is purely accretional. Typical depth: 5-40+ m.



Columnar *Porites* colony in Ras Al-Qasabah. Only the tops of the lobes are live.



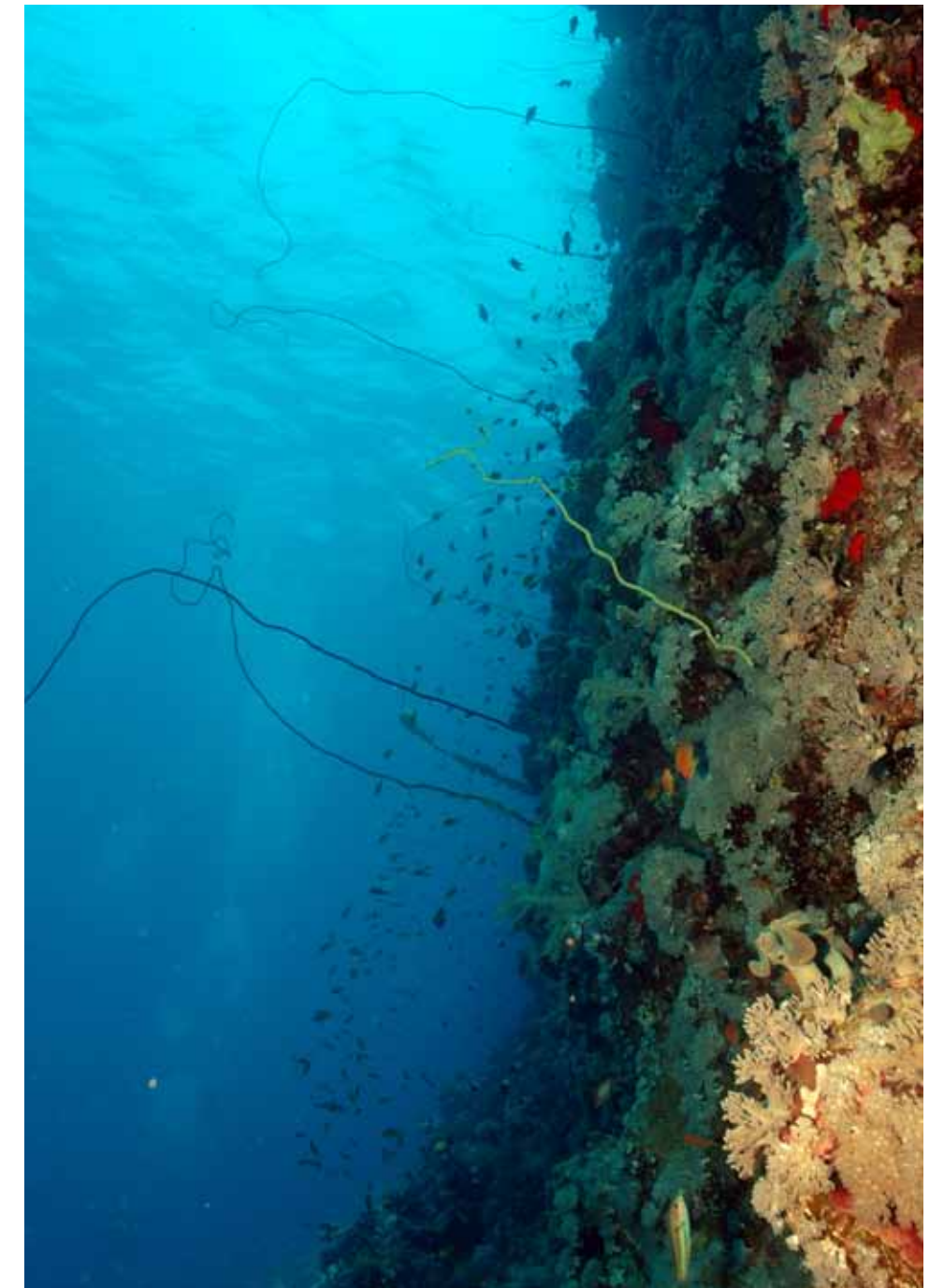
Typical columnar *Porites* framework at the base of a shallow reef in Al Wajh, 12 m depth.



Large living colonies of *Porites lutea* in the Farasan Banks. Scale bar is 1 m in length.

## Reef walls/drop-offs

Steep, near-vertical wall with coral cover ranges from 10-70%. All coral forms are present, but mainly encrusting and foliose growth forms on exposed points. Coral community consists mainly of species of *Pachyseris*, *Echinopora*, *Mycedium*, *Favia*, *Favites*, and *Millepora*. Space between coral colonies can be bare or occupied by sponge, macro-algae, coralline algae, *Xenia* and other species of soft coral. Low-relief grooves run sporadically down the vertical reef face. Coarse rubble debris originating from the reef crest accumulates at the base of these furrows. Typical depth: 3-40+ m.



Vertical wall on an offshore island near Al Wajh. The wall is carpeted in soft corals (predominantly *Xenia* spp.) with isolated sea whips (antipatharians).

## Dense *Acropora* thickets

Dense *Acropora* thickets are found on inner protected lagoonal patch reefs, shallow terraces with low-to-moderate wave exposure and exposed fringes and ledges. These areas are characterized by dense patches of interdigitated coral branches, often with multiple canopy layers. Live coral cover is typically 40-80% but may exceed 100% as a result of the canopy layers and dense branching patterns. The community is diverse but often is dominated by *Acropora clathrata*. Typical depth 5-15 m, although much shallower (1-3 m) in turbid areas.



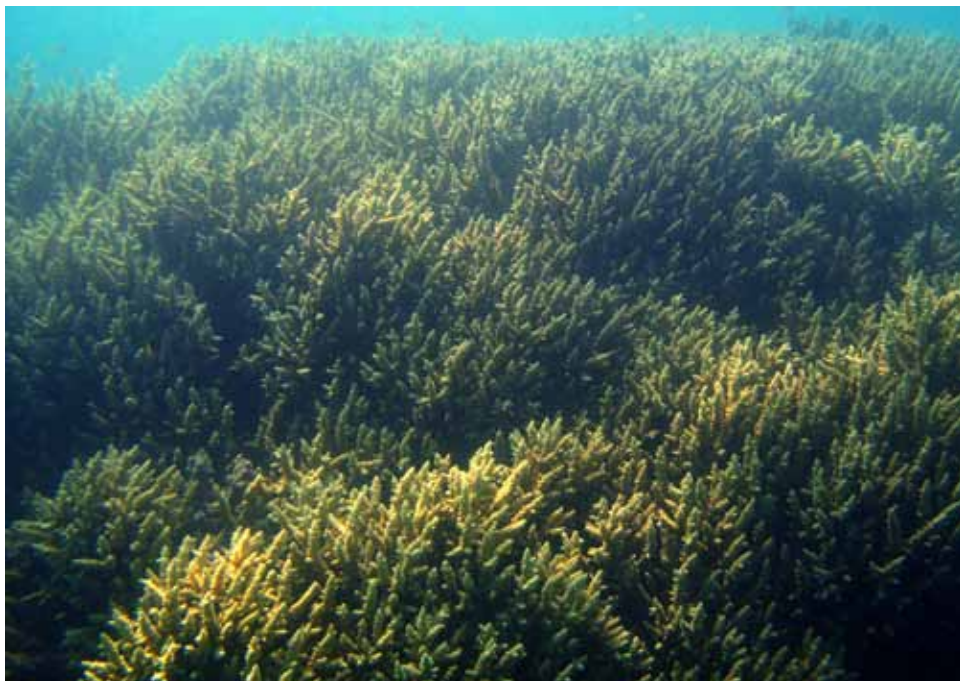
Dense thicket of *Acropora* spp. on an outer reef slope in the Farasan Banks.



Overlapping canopy layers of table acroporids, Farasan Islands, 10 m depth.



Thicket of digitate *Acropora* spp. on a leeward reef crest, Farasan Banks.



*Acropora* thicket on a shallow (2 m depth) lagoonal reef in Al Wajh Bank.



Mixed community of *Acropora* spp. on a shallow (5 m) patch reef in Al Wajh.



Branching acroporid community, leeward reef, Farasan Banks, 7 m depth.

## Scoured channels

Flat-relief hardground is found with a sparse community of soft coral (predominantly *Xenia*), *Padina*, and other macroalgae, as well as small, isolated hard corals of low diversity. Tidally driven water moves through narrow channels between lagoons and the open ocean. This high velocity flow removes unconsolidated sediment and scours the seabed. Typical depth: 1-20m.



A scoured channel between high-relief reef habitat off Yanbu, 14 m depth. These habitats often are found at the base of the reef. The substrate typically contains a thin veneer of sand, dead corals, and rubble with very little living coral.

## Carbonate hardground and reef flats

Hardground areas are below low tide line or emergent at low tide. Centimeter-thin veneers of sediment, small patches of macroalgae, small isolated corals, and filamentous turf algae occur. Exposed flats are largely devoid of sediment with algal turfs in areas of moderate exposure, primarily at the edges of coral and in depressions. Offshore reef flats, in areas with high wave action and strong currents, have low cover of macroalgae and sparse, small coral colonies of *Pocillopora* and *Stylophora*. Nearshore reef flats, especially around the Farasan Islands and Banks, may be colonized seasonally by brown macroalgae, including *Sargassum* and *Dictyota*. Protected reef flat communities may also be colonized by flattened colonies of *Acropora*, *Millepora*, *Stylophora*, *Porites* and other low-relief corals. Shallow exposed fringes may exhibit a 1-2 m raised rampart of calcareous red algae (CCA). Typical depth 0-1m.



Examples of reef flat communities in the Red Sea. A. Exposed outer reef flat in the Farasan Banks with isolated *Stylophora* colonies. B. Raised rampart of crustose coralline algae with brown macroalgae on a nearshore reef flat in the Farasan Banks. C. Reef flat community on Al Wajh barrier reef with *Millepora*, *Pocillopora*, and other corals. D. Reef flat in the Farasan Islands. Massive *Porites* colonies are competing with brown macroalgae. E. Reef flat community off Yanbu, with a dominance of plating *Acropora* colonies.



## Mangroves and nearshore vegetation

Mangroves are found throughout the Red Sea, occurring mainly in sheltered areas behind reef flats, in bays or creeks, and on the leeward side of offshore islands. In most locations, mangroves grow as relatively thin forests along the shoreline, on near-and offshore islands, and at the margins of fringing tidal creeks and channels of various size. The largest concentrations of mangroves are found in inner protected lagoons and sheltered embayments where water depths range from 0.5-1.5 m, especially in the south.



*Avicennia marina* and other coastal vegetation, Farasan Banks.



*Avicennia marina* tree and pneumatophores at the water's edge, Al Wajh.



Typical coastal vegetation seen on offshore islands in the Farasan Banks.

## Seagrass meadows

Seagrass beds occur in leeward and protected environments behind islands, close to shore, and at the base of leeward reefs. Most are in soft-bottom habitats in shallow waters, atop muddy organic-rich carbonate sands, at generally less than 7 m depth; some species of seagrass occur in deep water (10-40 m depth).



Closeup of *Halophila* seagrass blades and rhizomes.

Several species, including *Thalassia hemprichii*, *Thalassodendron ciliatum*, *Halophila ovalis*, and *H. uninervis* form dense monospecific assemblages. Mixed assemblages of seagrasses dominated by *T. hemprichii*, *Cymodocea rotundata*, *Syringodium isoetifolium*, and *H. stipulacea* were also observed. Patch density of grasses ranges from <5%-60% cover, and they often were intermixed with green and brown macroalgae. In shallow environments, dense patches (>50% cover) of seagrasses are relatively small in size (5-10 m<sup>2</sup>), while at depths below 10 m, such patches may be more extensive. Typical depth: 1-10 m, to 40 m in clear water.



Sparse seagrass bed dominated by *Syringodium isoetifolium* located at the base of a reef at 8 m depth, Ras Al-Qasabah.



A dense monospecific bed of *Thalassia hemprichii* seagrass exposed at low tide.

## Shallow sand sheets

Unconsolidated sand sheets consist of debris from corals, calcareous algae, Molluscs, and echinoderms. Meter-scale patches of macroalgae (e.g., *Laurencia*, *Caulerpa racemosa*, *Cladophora*) and sediment-resistant corals, such as *Favia* spp., are seen. In areas of low energy, sands may be covered by sparse, meter-scale algal mats (*Rhizoclonium tortuosom*, *Chaetomorpha gracilis*, *Cladophora coelothrix*). Typical depth: 0-20 m.



Shallow subtidal sand flat located off an island in the Farasan Banks.



Sand flat at the base of a reef, 15 m depth, Al Wajh Bank. Small corals and dead coral fragments occur on the substrate.

## Cyanobacteria mats on sand

Extensive cyanobacteria or filamentous algal mats dominated by *Rhizoclonium tortuosom*, *Chaetomorpha gracilis*, and *Cladophora coelothrix* were found in sandy areas most commonly in protected environments, especially on the leeward side of islands and in nearshore areas. These also occurred at the base of the reef in some areas. Typical depth: 1-40 m.



Cyanobacterial mats on sand and coral rubble in a lagoonal environment.

## Deep lagoonal sands

Fine, skeletal coralgall sand and mud, as well as sporadic patches of seagrass (predominantly *Cymodocea serrulata*); green calcareous macroalgae; such as *Halimeda*, coral rubble, and coral frameworks; and occasional colonies of *Xenia* are found. An absence of living corals or very low live coral cover are seen. Typical depth: 20-40 m.



A deep (15 m) sandflat in Ras Al-Qasabah with an absence of coral and algae.

## Sand and mud flats

Skeletal coralgall sand and mud sediment commonly exposed are found at low tide. Sediment depth varies. Where sediment is thin, meter-scale patches of hard or semiconsolidated substrate covered with a thin veneer of filamentous or calcareous macroalgae are seen. Semiemergent areas may form sabkhas (salt flats). Typical depth: 0-1 m.



A mud flat in a protected nearshore environment at low tide, Al Wajh Bank.



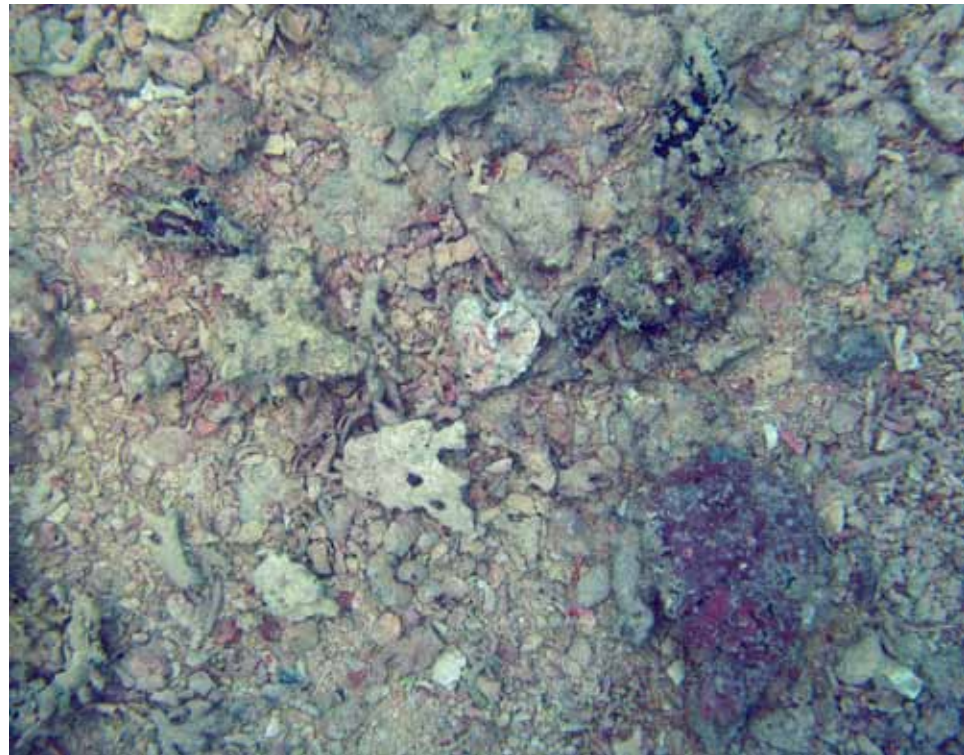
A sand and mud community located adjacent to the shoreline in Al Wajh. Macroalgae, diatoms and cyanobacteria occur on the substrate.

## Sparse corals, rubble, and sand

An unconsolidated matrix of coarse sand and coralline rubble is found down-slope from live coral crests or deposited inshore in moderately sheltered areas. Areas may be predominantly rubble with an absence of live coral, sand with patches of rubble and small corals, or sand with isolated coral heads and small sponges. Sediment may be cemented by coralline algae or sponges, allowing for some coral colonization, leading to a sparse coral community composed mainly of species of *Favia*, *Favites*, *Fungia*, *Acropora*, and *Xenia* (soft coral). Typical depth: 3-10 m.



Small dead coral heads in sand at the base of a reef, Farasan Banks, 10 m depth.



Rubble, coralline algae and coral fragments at the base of a reef, Al Wajh.



Pavement with sediment, rubble, and isolated sponges, Farasan Islands, 8 m depth.



Green macroalgae at the base of a reef on sand, Farasan Banks, 10 m depth.

## Macroalgae and sponges on sandy hardgrounds

Reef flats and other hard substrates in southern regions and also certain subtidal soft bottom habitats throughout the Red Sea are dominated by macroalgae. Algal cover drops precipitously from 50-90% in 1-4 m depth to <5% cover at depths greater than 5 m. Reef flat communities, platform reefs, and other shallow marine habitats often contain hardground areas interspersed with patches of sand that are colonized primarily by macroalgae and sponge assemblages. In shallow habitats (0-5 m), *Sargassum* and *Padina* are dominant and typically found in equal proportions. Patches are 1-5m in diameter, <50 cm height, and separated by less than 1m of sand on platform tops. Deeper areas (5-15 m) are dominated by *Sargassum* and *Padina* on a limestone substrate and are often intermixed with *Drysidea* sponges, *Xenia* soft coral, and small isolated stony corals. Typical depth: 1-15 m.



*Dictyota* and other brown algae on a nearshore reef flat, Farasan Banks, 1 m depth.



*Padina* and *Sargassum* macroalgae on pavement, Farasan Islands, 1m depth.

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## Habitat Maps of Saudi Arabian Red Sea



## Ras Al-Qasabah





Above: Beachrock in the northern Red Sea near Ras Al-Qasabah. Beachrock forms so-called imbricate layers (dipping seaward) and consists of cemented beach sand. These rocks only form in the intertidal zone and are therefore useful for delineating ancient shorelines or sea levels. The uppermost layers can erode strongly, as is seen in the right foreground. These erosional features are called karst.

Opposite page, left: Location of Ras Al-Qasabah. Source of basemap: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

Opposite page, top right: Sedimentary strata at Ras Al-Qasabah. Their strong dip toward the Red Sea basin is partly due to uplift, partly original morphology. The thicker strata contain fossil reefs, and thinner strata are shallow water sandy sequences.

Opposite page, bottom right: A raised limestone coast near Ras Al-Qasabah. Extensional pressures along the Red Sea graben force the coastlines upward, exposing marine sediments deposited in earlier epochs. Also paleo-sealevel highs are recorded in raised limestone, up to five such terraces, exist in the northern Red Sea.

## Ras Al-Qasabah

Ras Al-Qasabah is located within the Midyan region, west of the Sinai Peninsula. The coastline near Ras Al-Qasabah is very intricate with headlands, wadis and gentle foothills, and numerous small bays with sandy beaches. Just off the coastline are several small islands. The two largest islands in the region are Al Farshah at the northern end and Umm Qusar at the southern end. There is also an offshore island, Burqan, surrounded by reef framework and deep water.

The region contains numerous coral reefs that are adjacent to the coastline and fringing offshore islands. These include reef-edged sharms at the edge of wadis, which flow down from Al Hisa mountains carrying sand and gravel. The litoral zone often contains alluvial sand flats extending along the shoreline in narrow belts up to 1 km wide. At the mouths of some wadis, salt marshes dominated by *Halocnemum strobilaceum* and dry sabkhahs may be found. Mangroves (primarily *Avicennia marina*) occur primarily around inlets and also occur, often in a stunted growth form, in rocky areas.

Marine habitats in Ras Al-Qasabah are highly variable and include coral reef frameworks, seagrass beds, subtidal sand flats, extensive soft coral areas, sand, and algal patches. Much of the reef consists of reticulated or “honeycomb” structures built on a framework of the massive coral in the genus *Porites*. These comprise strings approximately 1-10 m across of living coral or coral skeletons surrounded by sand and rubble patches. Extensive *Thalassodendron* seagrass beds are located in deep-sandy environments, typically at 15-25 m.



Characteristic fore reef community at Ras Al-Qasabah composed primarily of large columnar lobate colonies of *Porites lutea*, the dominant framebuilder in the region. These are often partially dead and are colonized by other corals, including *Acropora*, and soft corals (*Xenia*), as seen in this photo.



Shallow reef community with small branching corals in the genus *Acropora*, *Seriatopora* and *Pavona*, free-living fungiid corals (*Fungia*) and soft corals.



Columnar growth forms of *Porites* form the framework of coral reefs throughout most of the Red Sea, including Ras Al-Qasabah's reefs. This coral has a massive growth form, increasing in size only a few cm per year. In much of the region, the coral has experienced extensive mortality due to abnormally high temperatures during 1998. Other stressors, such as predation by crown of thorns sea stars, have contributed to further losses of this coral. On most reefs examined in the region, only shallow areas (3-5 m depth) still contain high cover of living corals (30-50%) while deeper areas are often 5-10% live coral or less. The *Porites lutea* colony shown above is about 50 cm tall and is mostly live. Two lobes have died and are colonized by an encrusting sponge, and a small branching coral (*Seriatopora*) has also settled on the *Porites* skeleton.



On some reefs, isolated boulder corals of a large size survived unusual periods of temperature stress, such as this colony of *Platygyra daedalea*.



*Porites* framework that is mostly dead and colonized by small branching corals and soft corals (foreground). A large (>3 m diameter) massive *Porites* colony is visible in the background.

Bottom right: On some offshore reefs extensive old mortality was apparent, but much of the reef framework was colonized by other branching corals, such as the *Acropora* colony in the foreground, small massive *Goniastrea* colonies, and lobate colonies of *Favia stelligera*, as seen on the top right.



Fire coral (*Millepora*) in the reef crest on a leeward reef (3 m depth).



## Ras Al-Qasabah Imagery and Habitat Maps

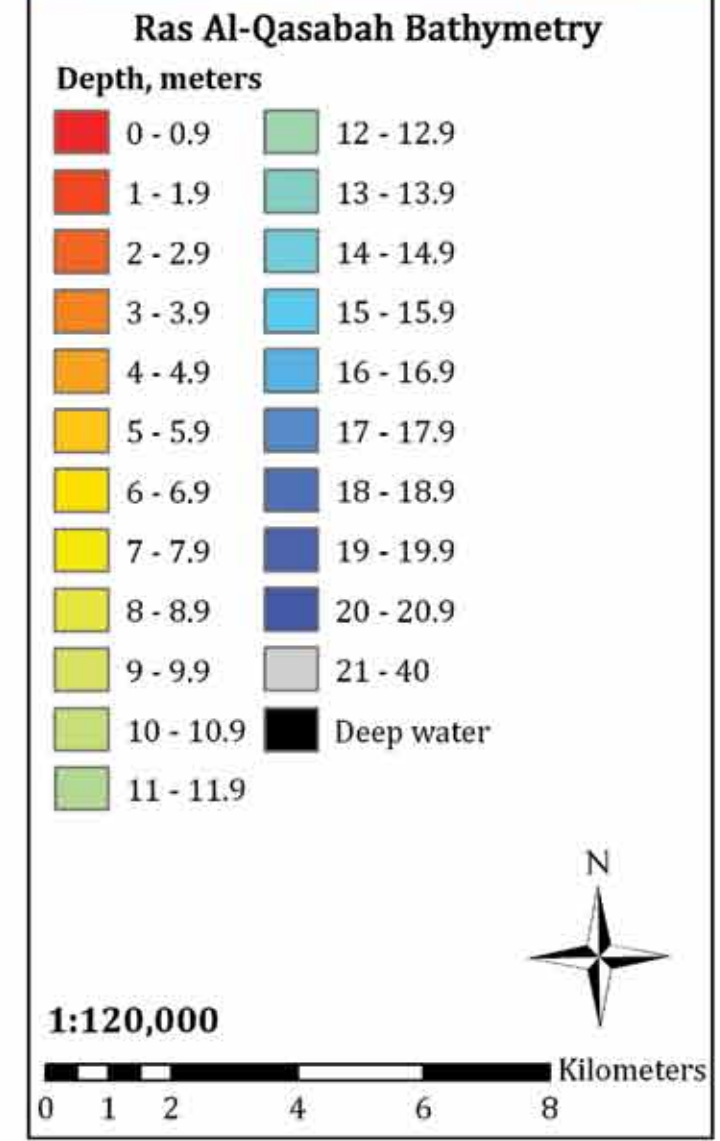
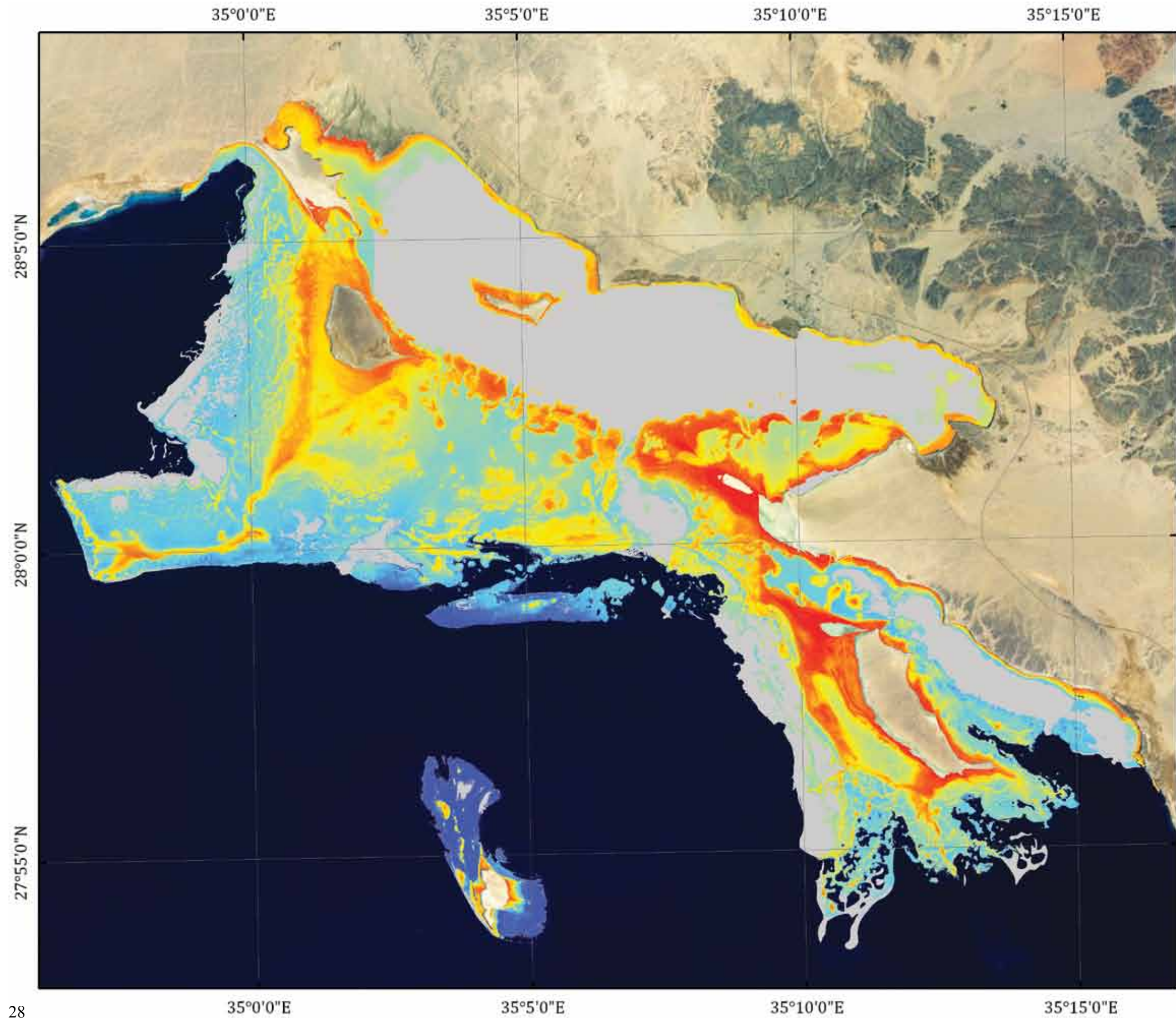
Satellite imagery, bathymetry, and habitat maps for Ras Al-Qasabah are illustrated on pages 27-51. A total of 290.6 sq km was mapped and subdivided into 12 shallow marine habitat classes with areas below 25 m depth depicted in dark blue as deep water.

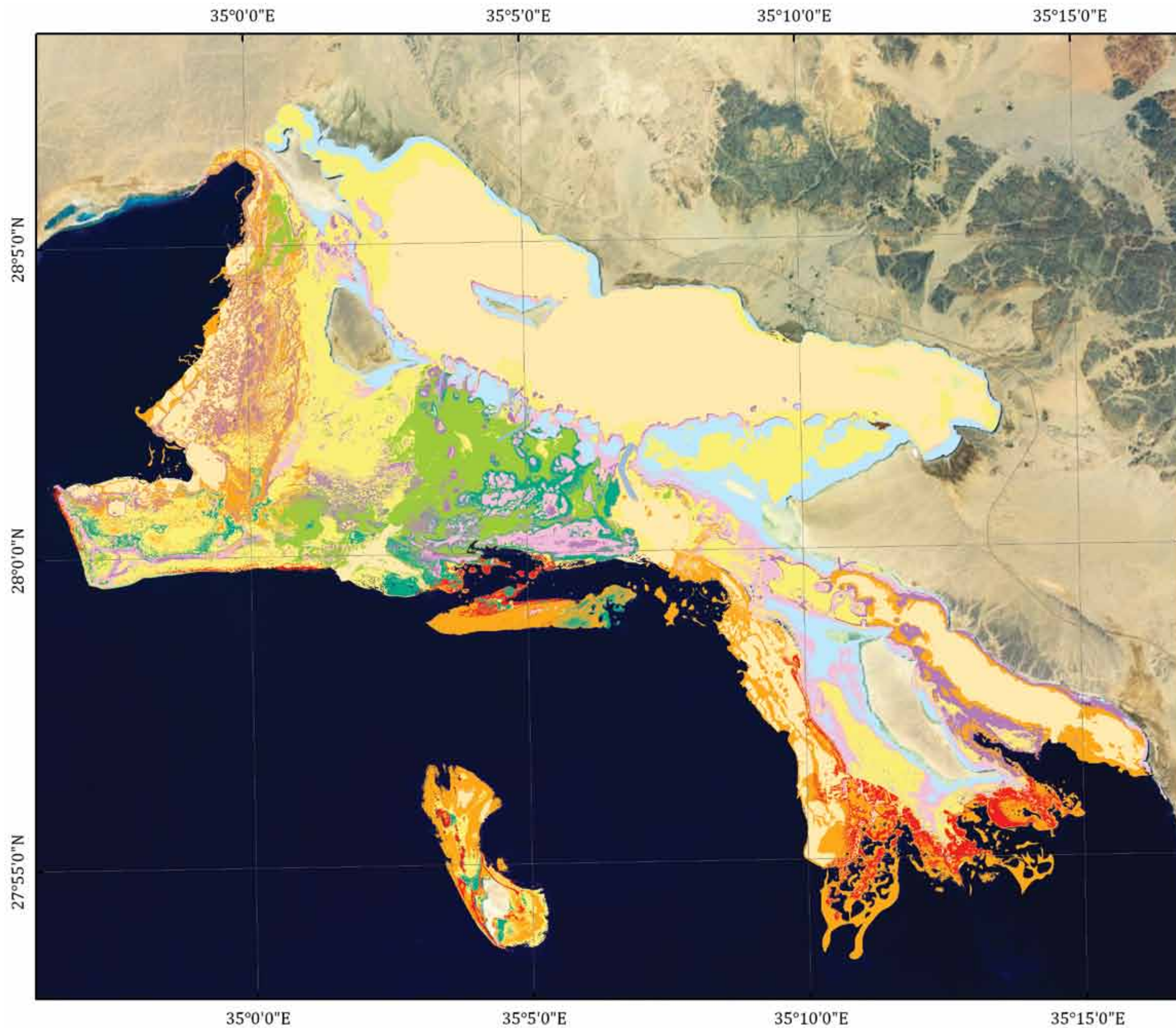
QuickBird multispectral satellite imagery of Ras Al-Qasabah (right), bathymetry (page 28), and a resulting habitat map for the same area (page 29) are shown at a scale of 1:120,000. A locator map for the habitat maps is on page 30. More detailed habitat maps (1:24,000) and bathymetric maps for representative areas within the Ras Al-Qasabah region are on subsequent pages. Each of the five 1:24,000 scale bathymetric maps included in this section is on the left (even-numbered) page and the habitat map for the same area is shown on the right (odd-numbered) page. Source of terrestrial basemap imagery used in all habitat maps and bathymetric maps is: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

A total of 290 sq km of shallow offshore habitats was mapped and subdivided into twelve different habitat types, six of which contain coral. Much of the coastal submerged habitat consist of a deep sand-bottom lagoon enclosed by a reef framework. Reef habitats also extend offshore and around the smaller offshore islands.

Ras Al-Qasabah Habitats	Total area (sq km)	% region total
Reef walls and drop-offs	0.22	0.10
Windward coral crests	7.89	2.70
Leeward coral crests	16.36	5.60
Columnar frameworks	39.87	13.70
Sparse corals, rubble, and sand	10.52	3.60
Seagrass meadows	17.78	6.10
Macroalgae, sponges, sandy hardgrounds	0.09	0.00
Scoured channels	0.72	0.20
Carbonate hardground and reef flats	21.05	7.20
Shallow sand sheets	66.54	22.90
Deep lagoonal sands	85.83	29.50
Sand and mud flats	23.75	8.20
<b>TOTAL AREA MAPPED</b>	<b>290.60</b>	<b>100</b>



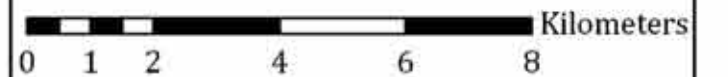


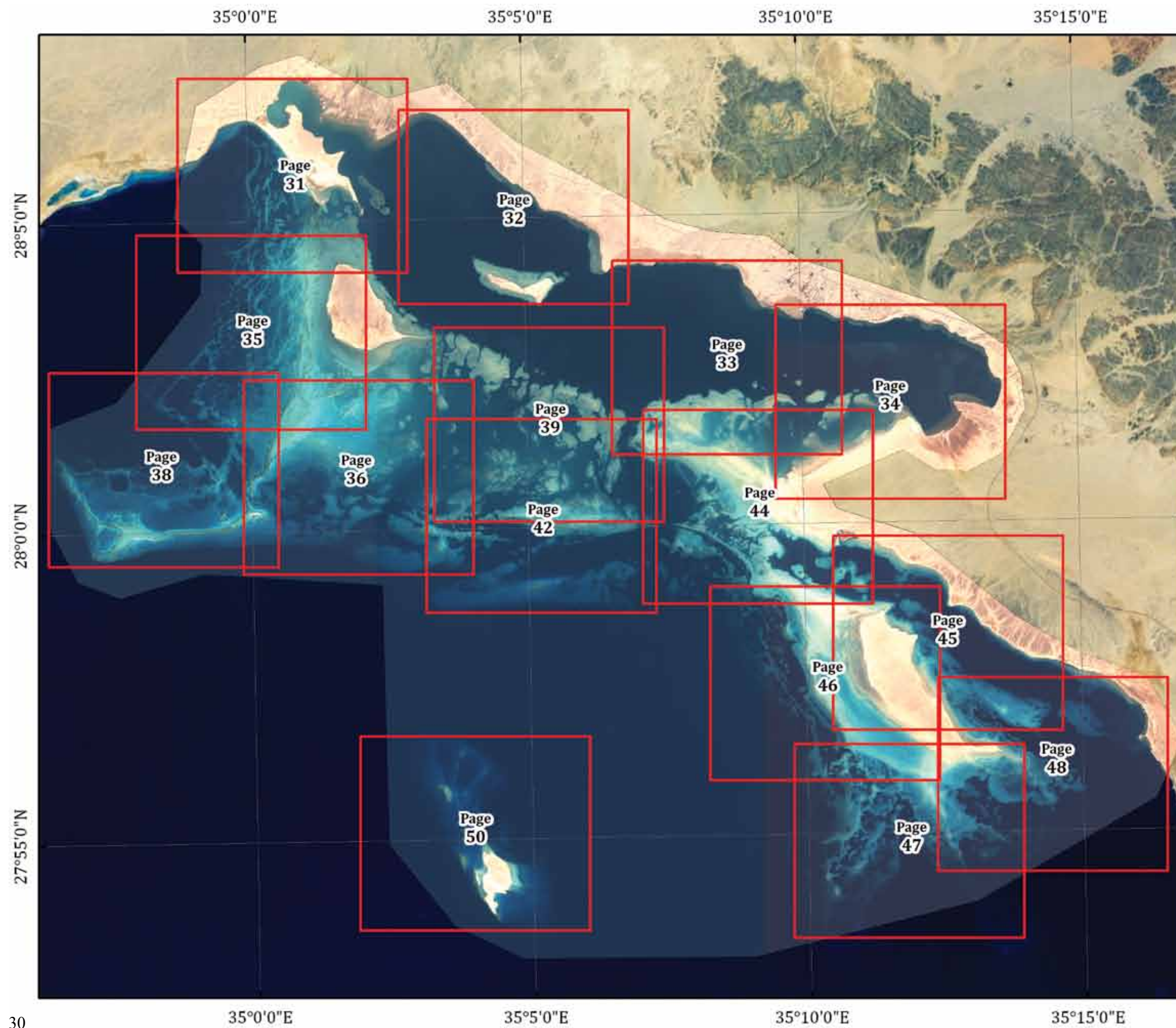


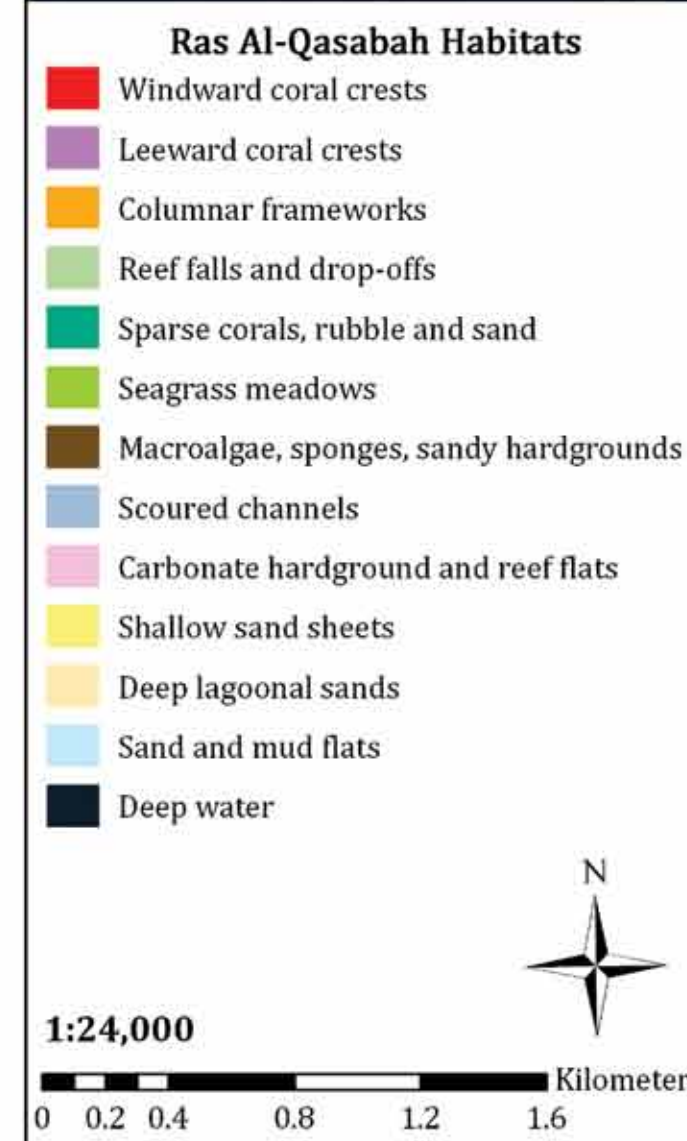
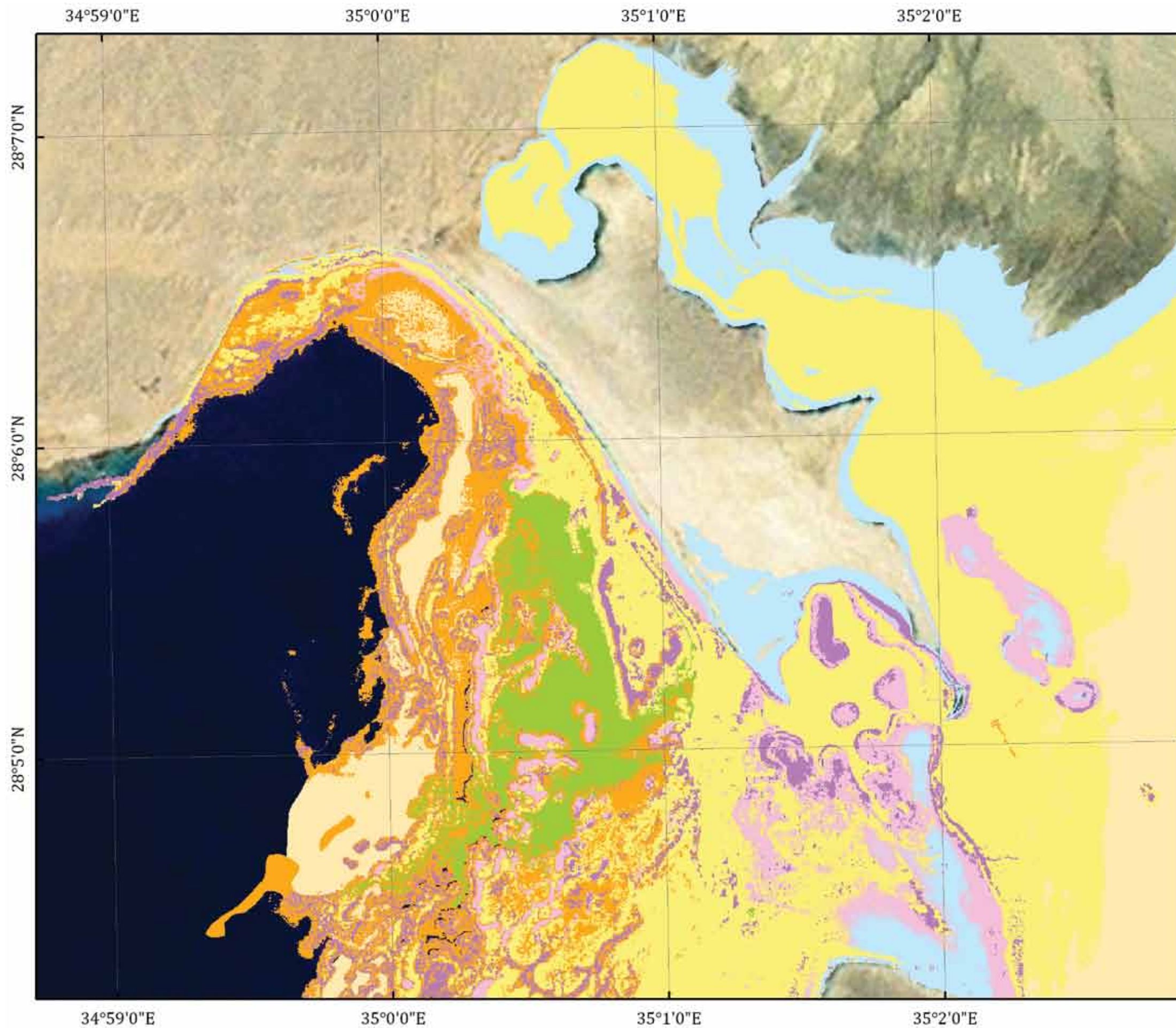
**Ras Al-Qasabah Habitats**

- Windward coral crests
- Leeward coral crests
- Columnar frameworks
- Reef falls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
- Macroalgae, sponges, sandy hardgrounds
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

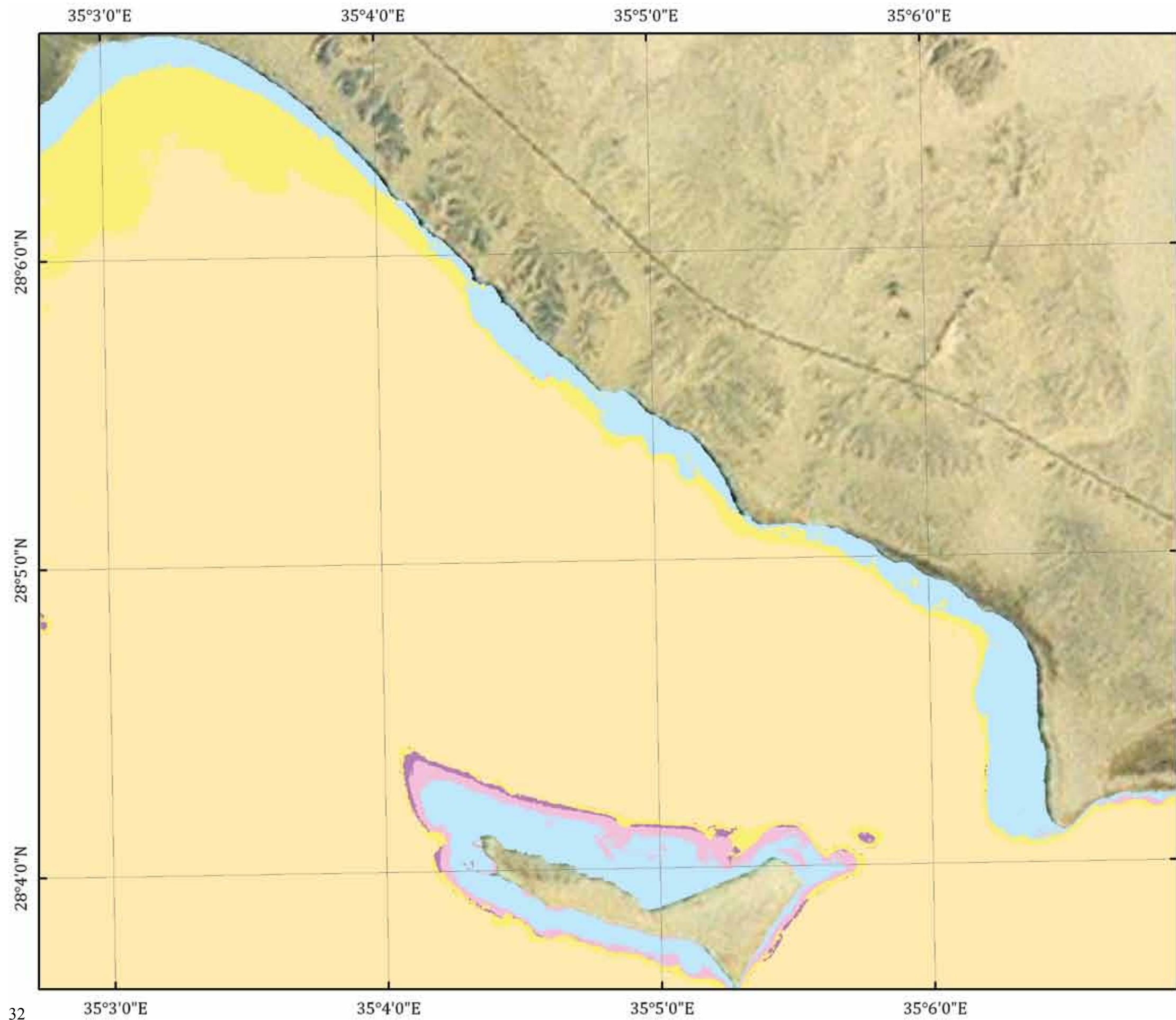
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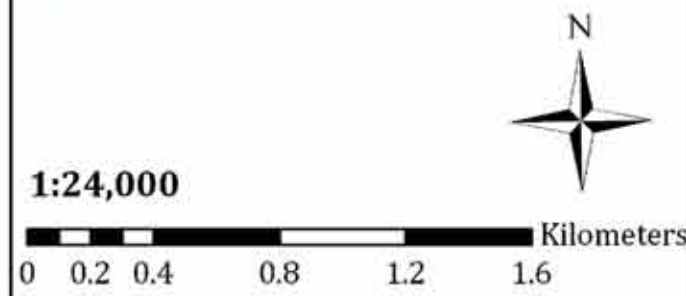


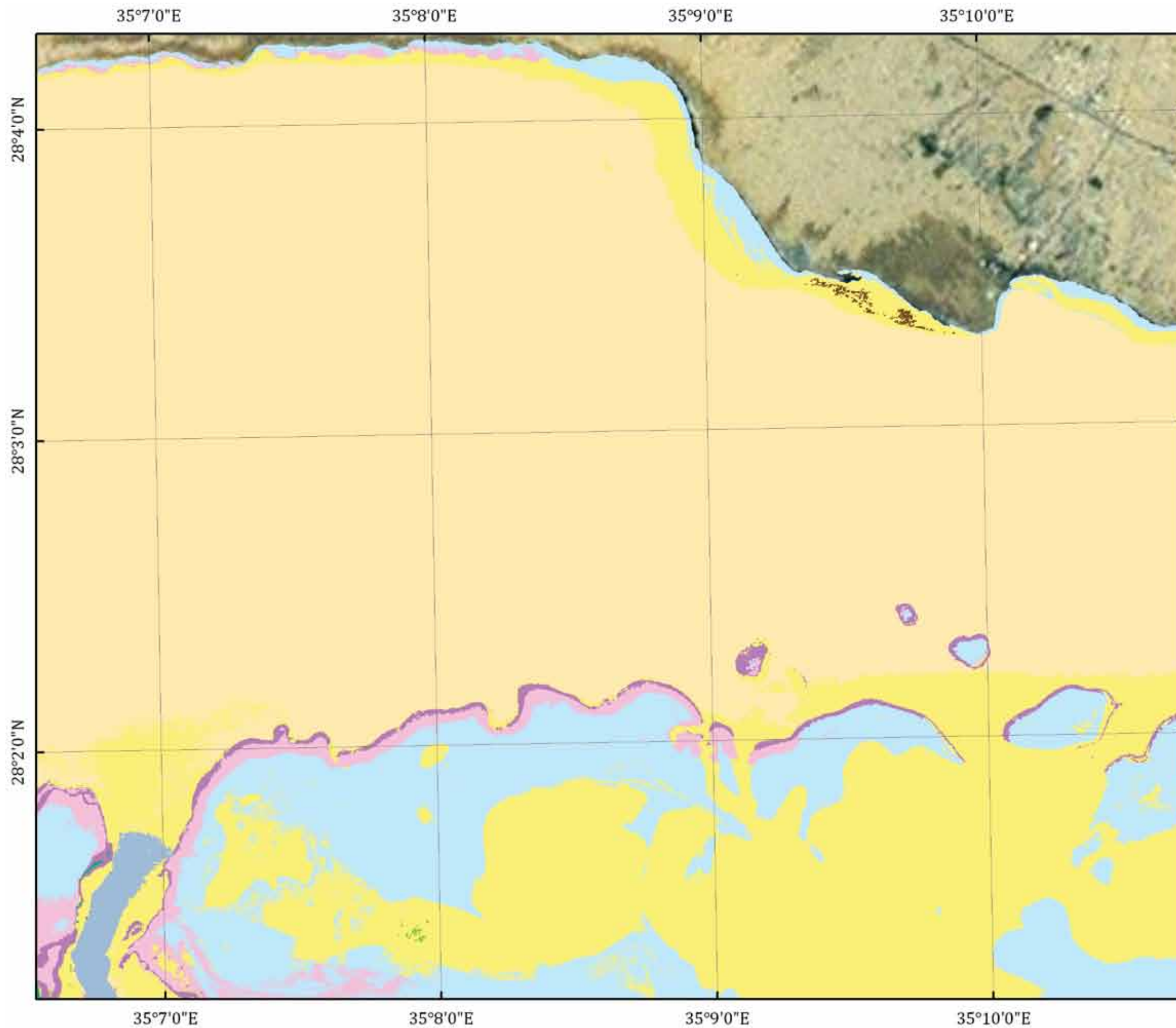




**Ras Al-Qasabah Habitats**

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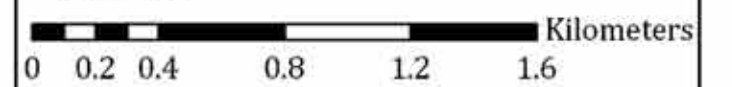


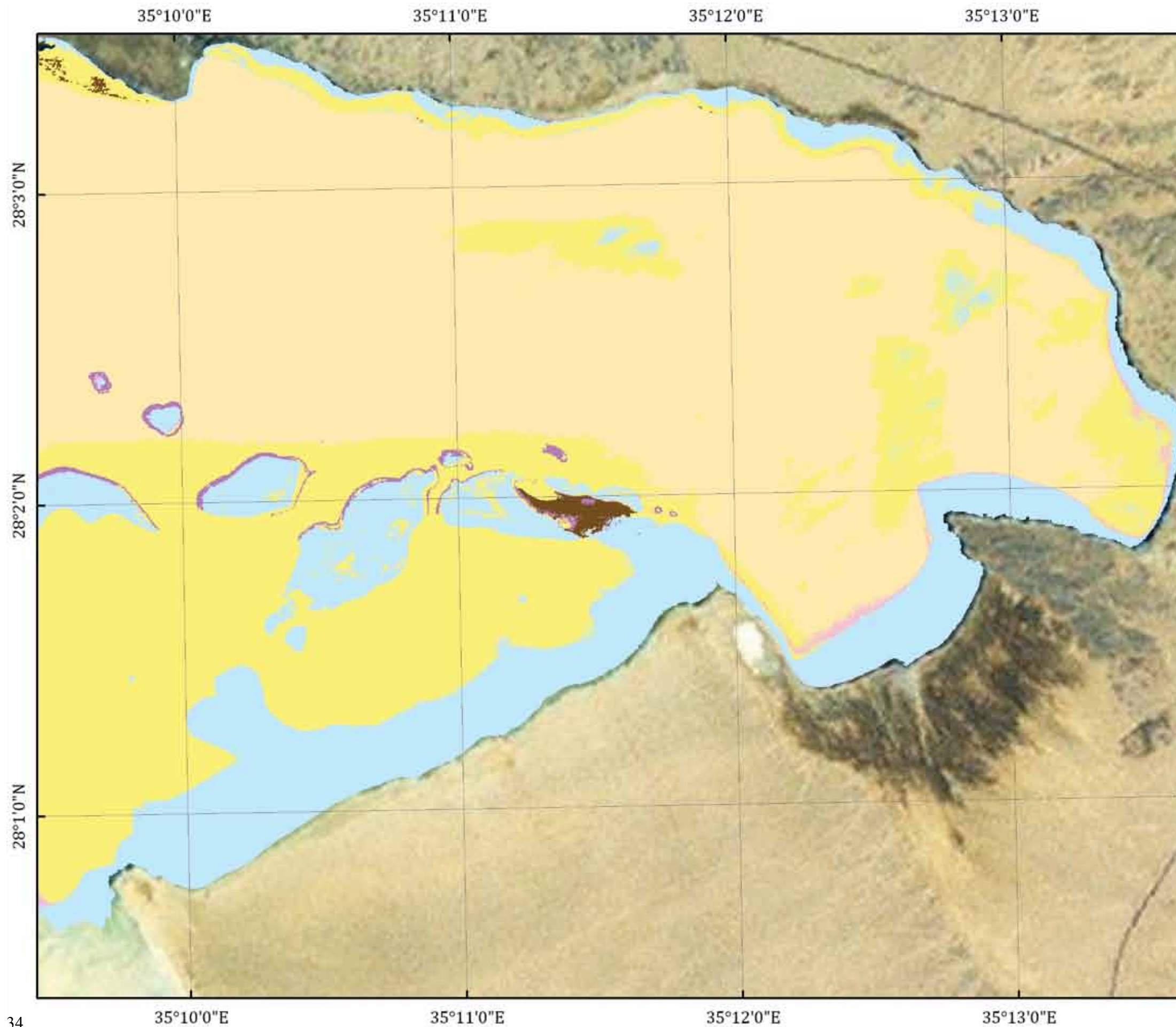


**Ras Al-Qasabah Habitats**

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**1:24,000**





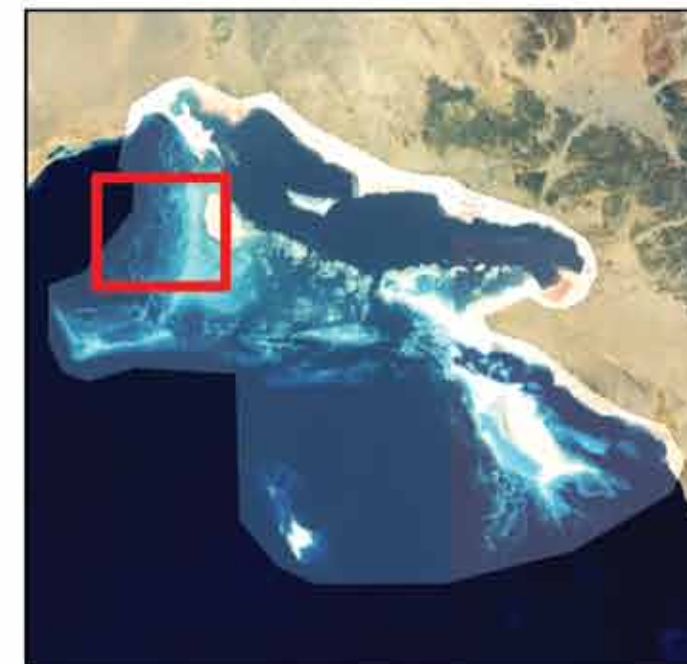
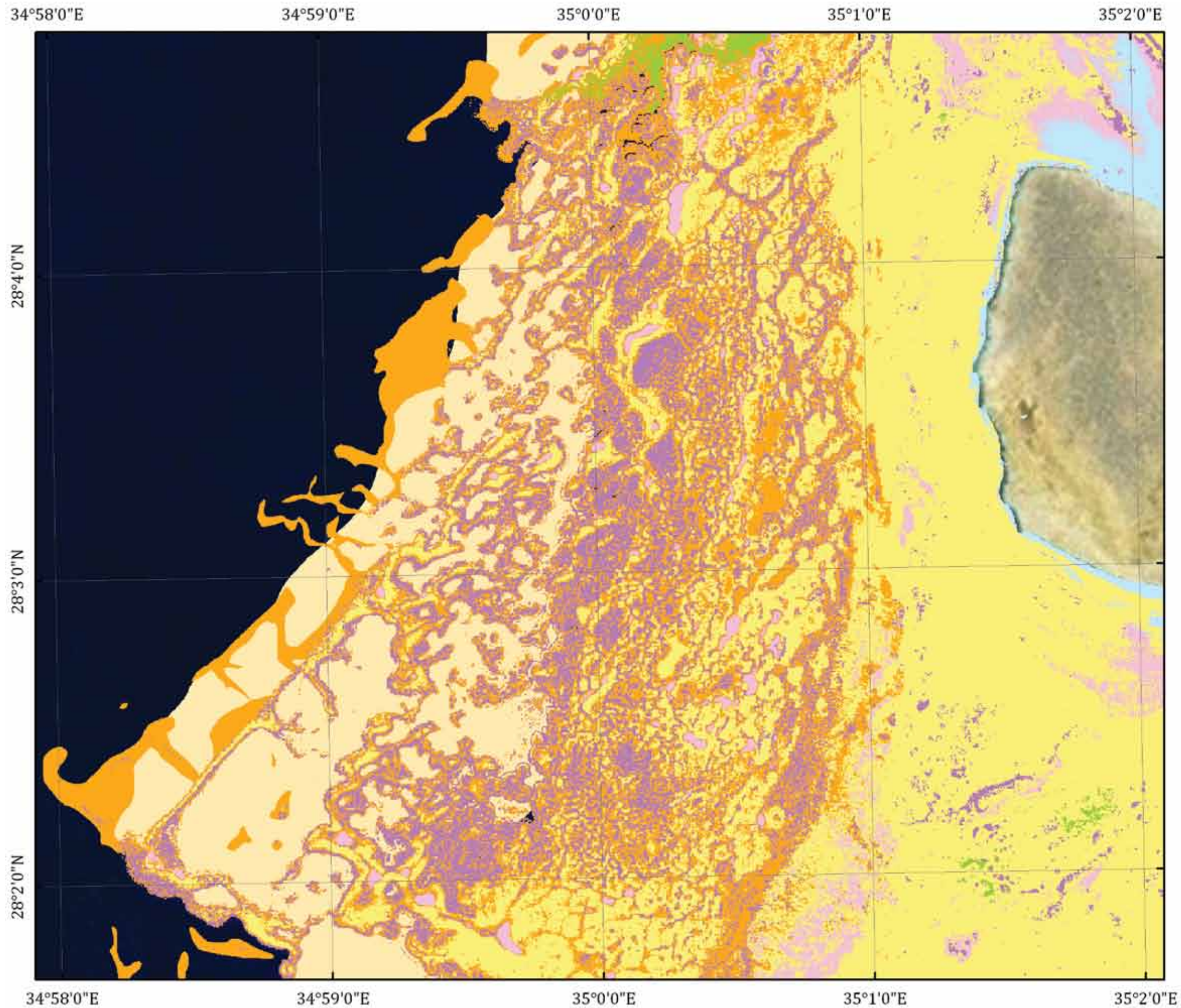
**Ras Al-Qasabah Habitats**

- Windward coral crests
- Leeward coral crests
- Columnar frameworks
- Reef falls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
- Macroalgae, sponges, sandy hardgrounds
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water



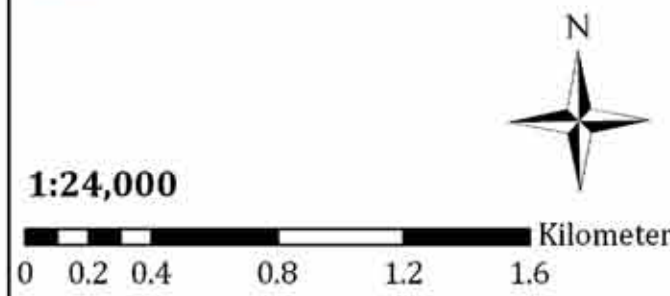
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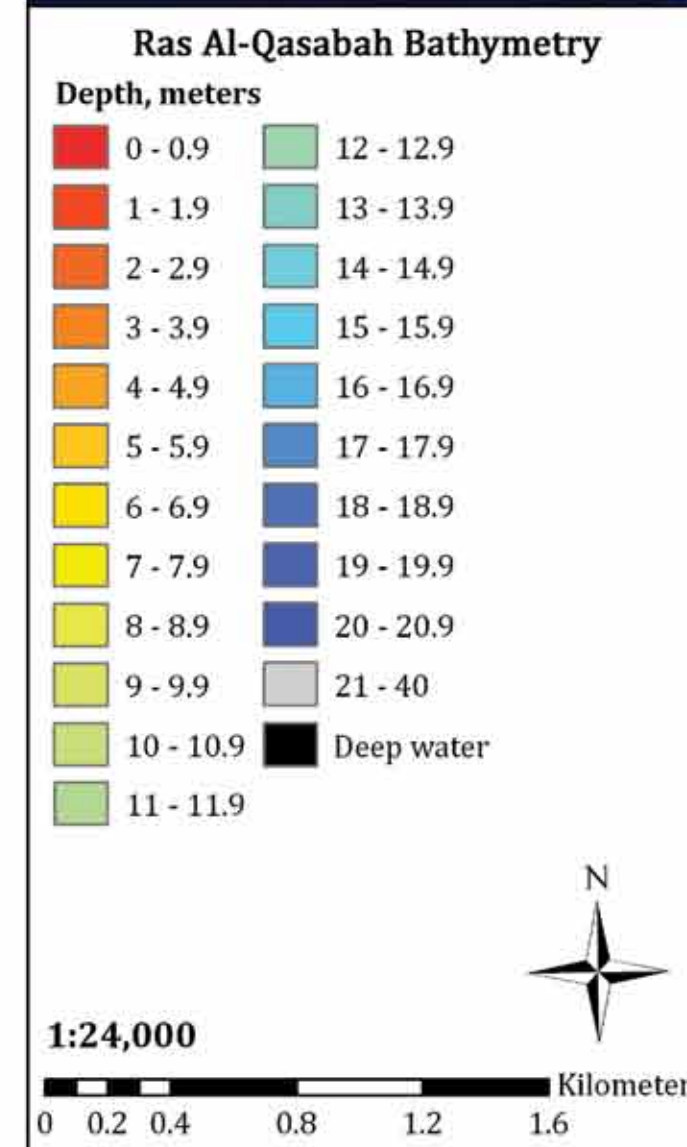
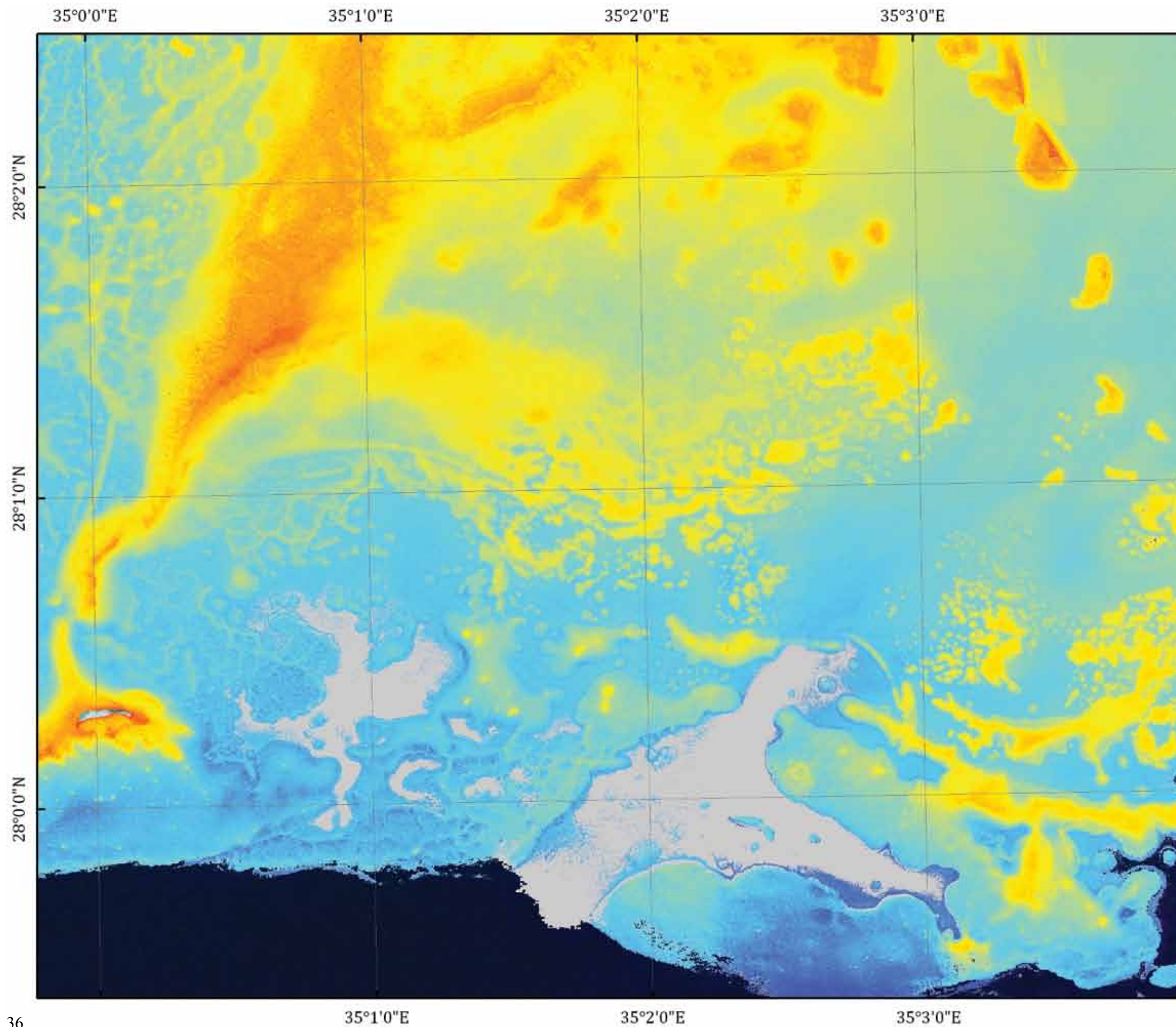


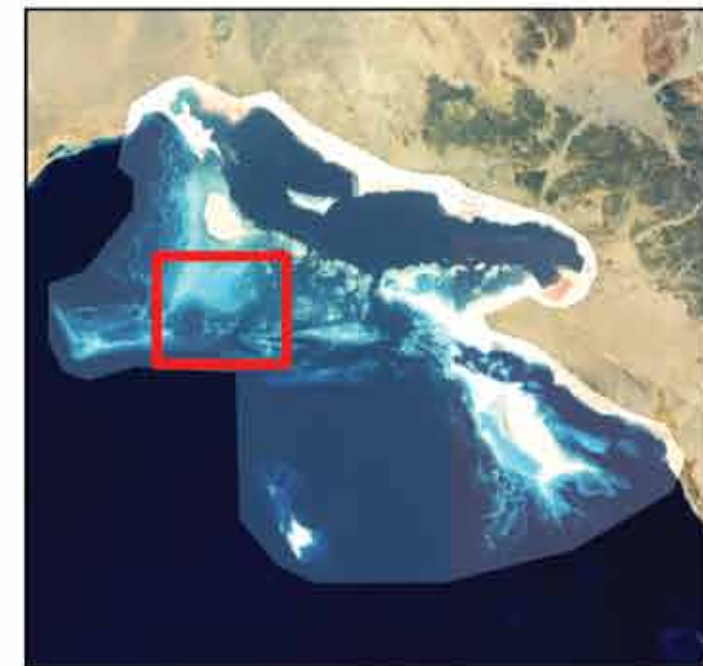
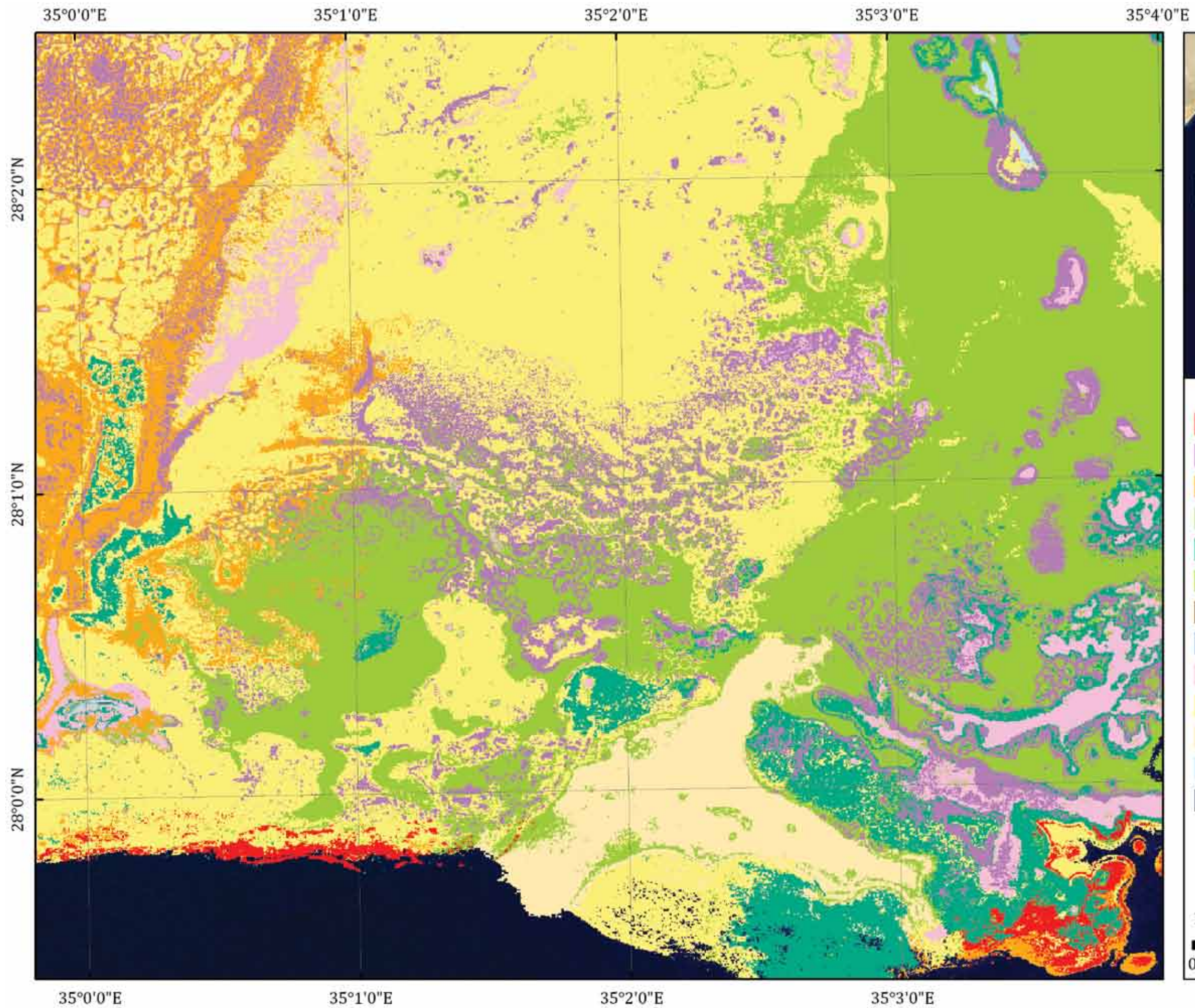


### Ras Al-Qasabah Habitats

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- Sand and mud flats
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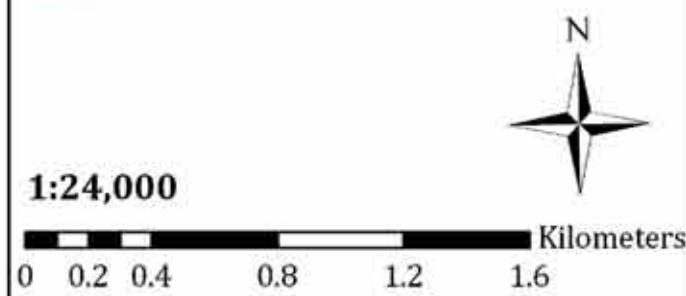


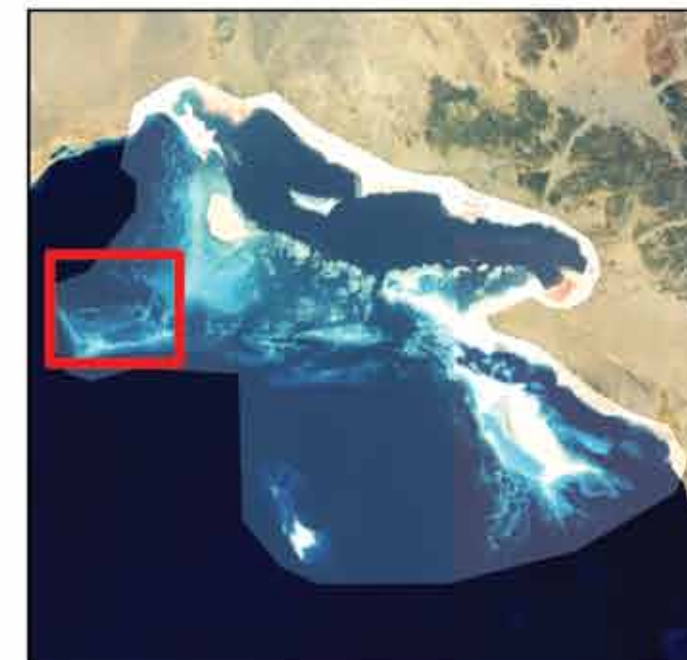
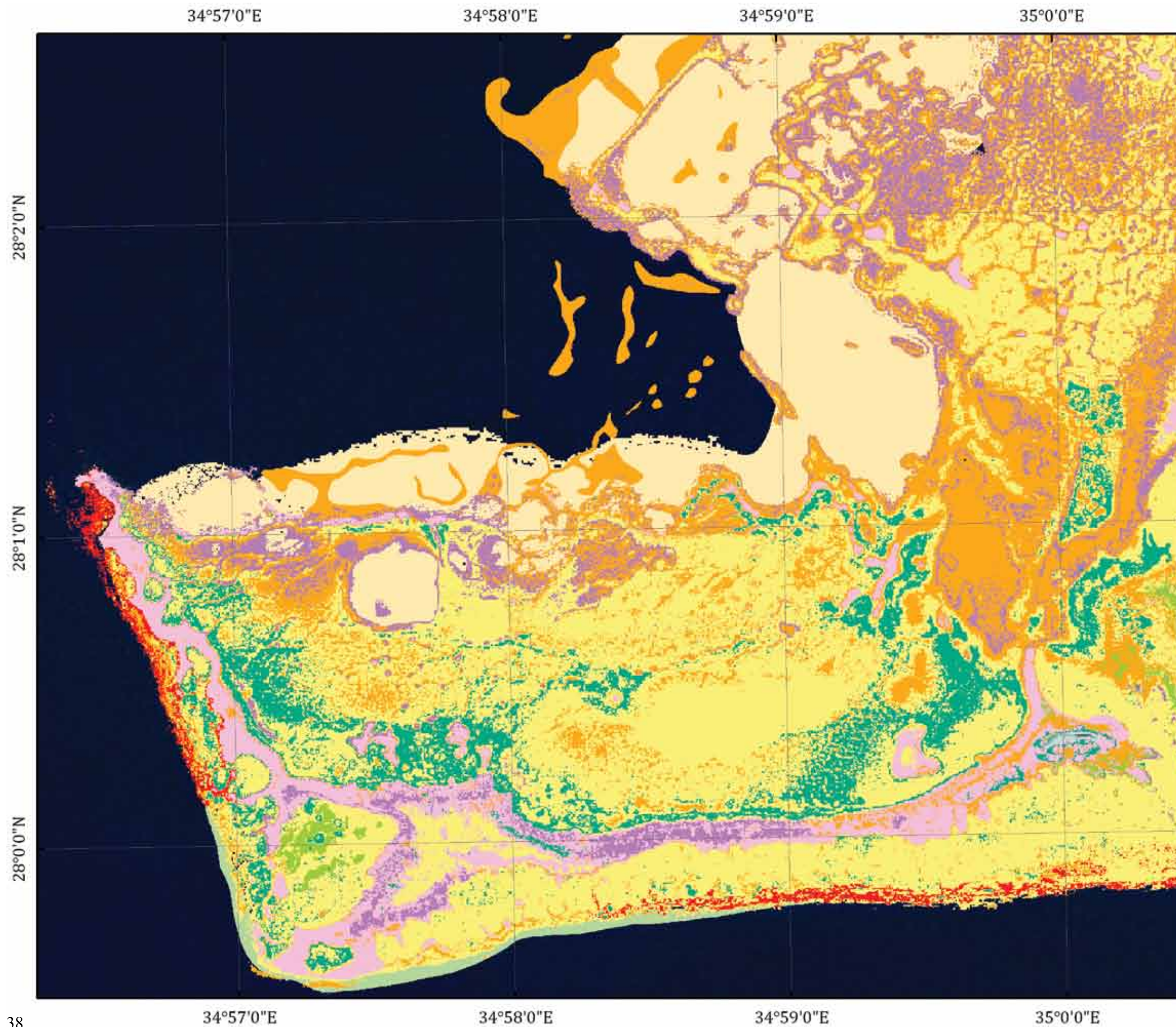




**Ras Al-Qasabah Habitats**

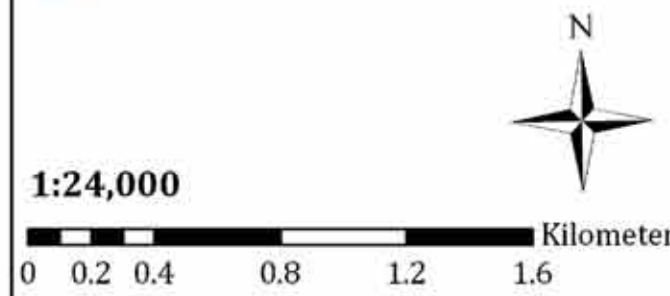
- Windward coral crests
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- Deep lagoonal sands
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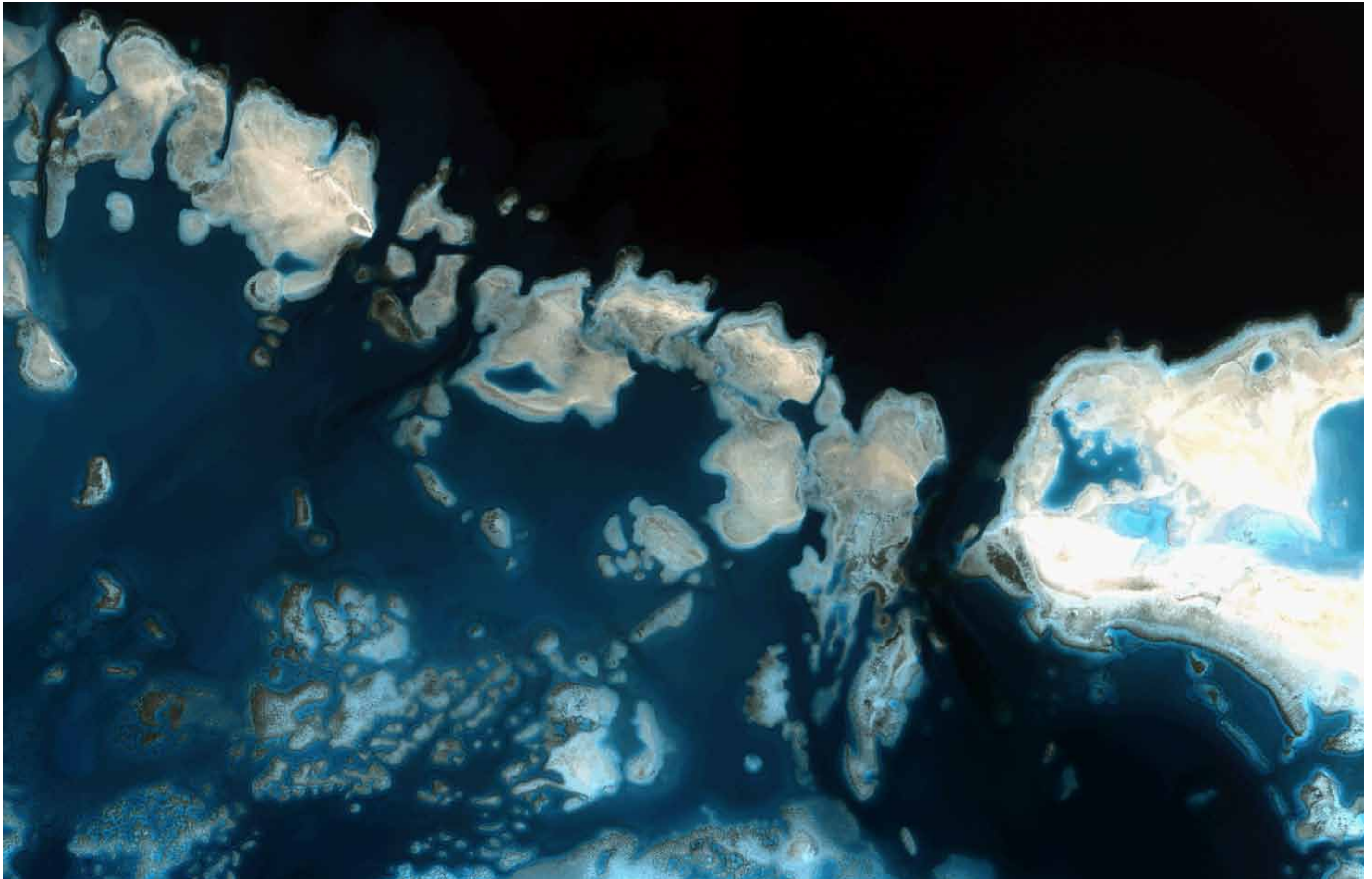




**Ras Al-Qasabah Habitats**

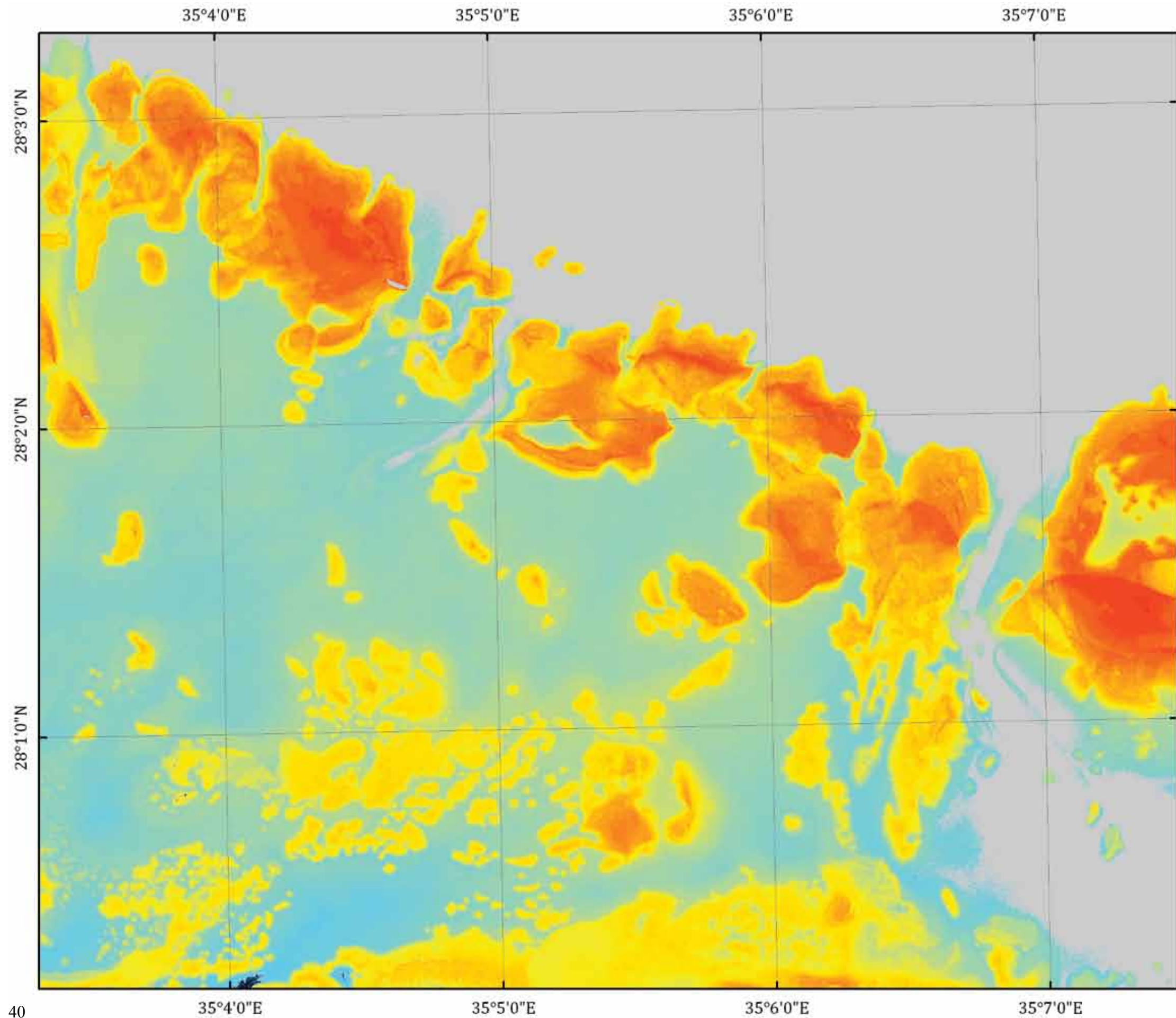
- Windward coral crests
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- Deep lagoonal sands
- Sand and mud flats
- Deep water





High resolution satellite image of offshore marine habitats at a scale of 1:24,000. Bathymetry and habitat maps for this region are on pages 40-41.





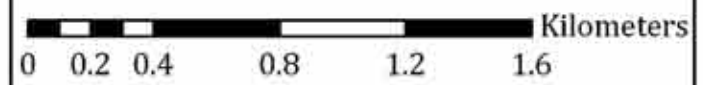
**Ras Al-Qasabah Bathymetry**

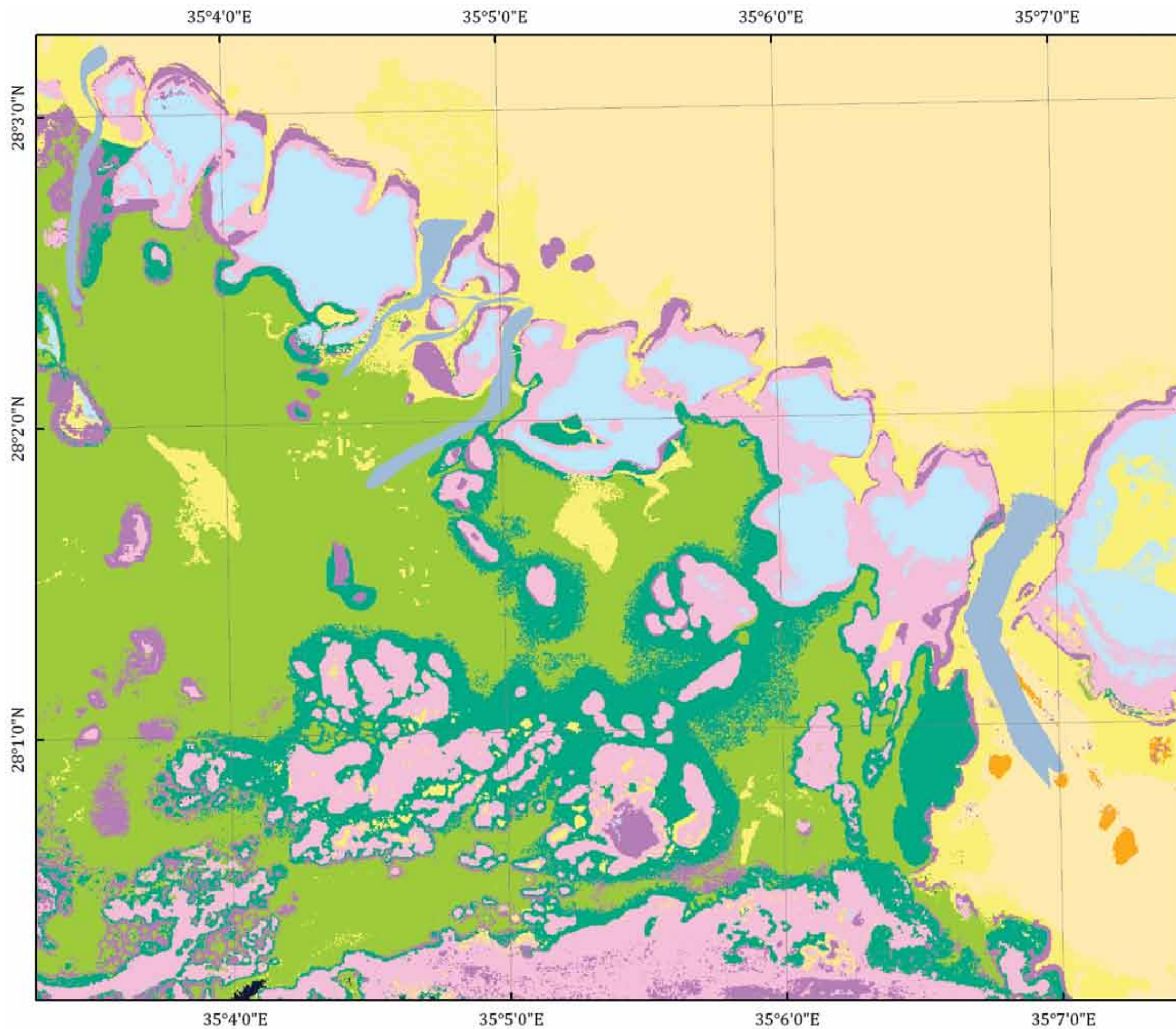
**Depth, meters**

0 - 0.9	12 - 12.9
1 - 1.9	13 - 13.9
2 - 2.9	14 - 14.9
3 - 3.9	15 - 15.9
4 - 4.9	16 - 16.9
5 - 5.9	17 - 17.9
6 - 6.9	18 - 18.9
7 - 7.9	19 - 19.9
8 - 8.9	20 - 20.9
9 - 9.9	21 - 40
10 - 10.9	Deep water
11 - 11.9	



**1:24,000**



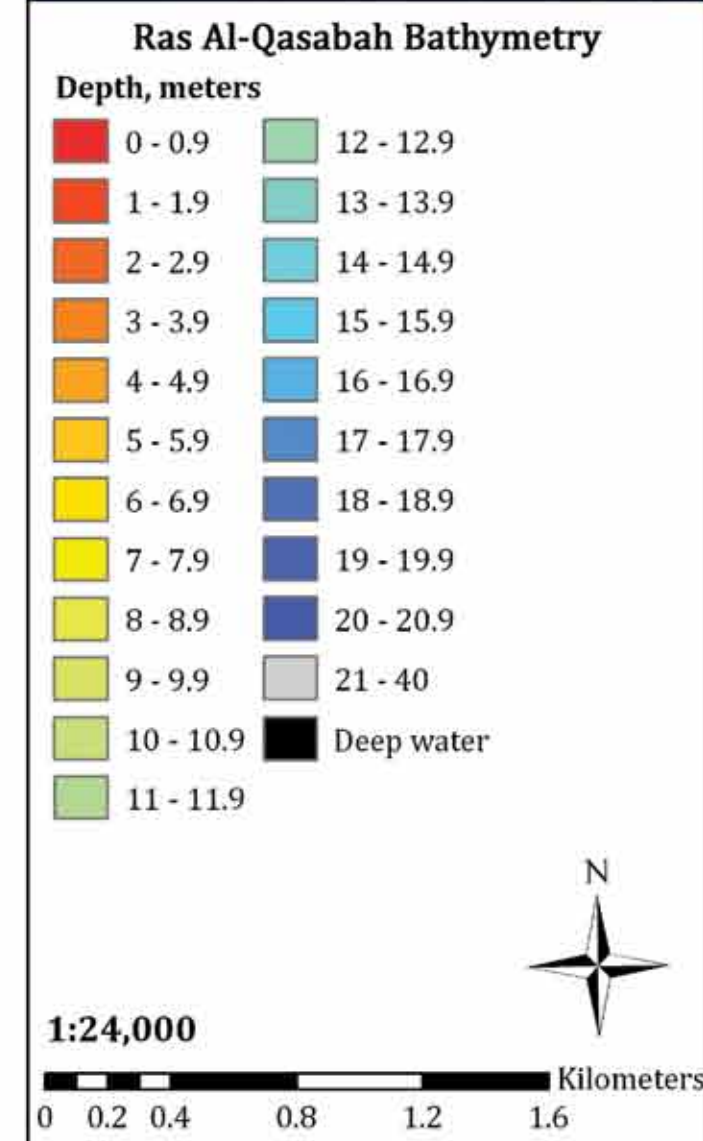
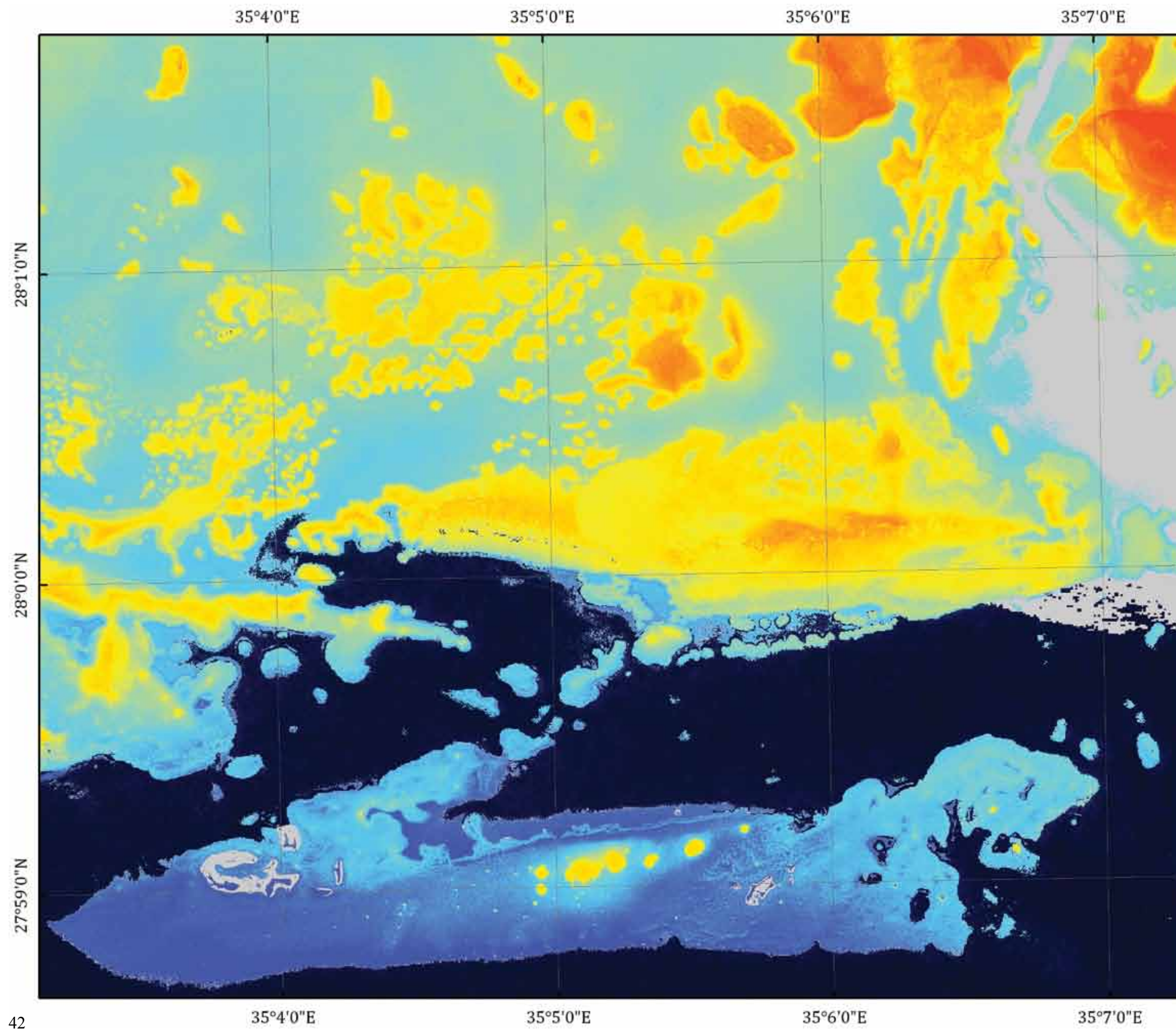


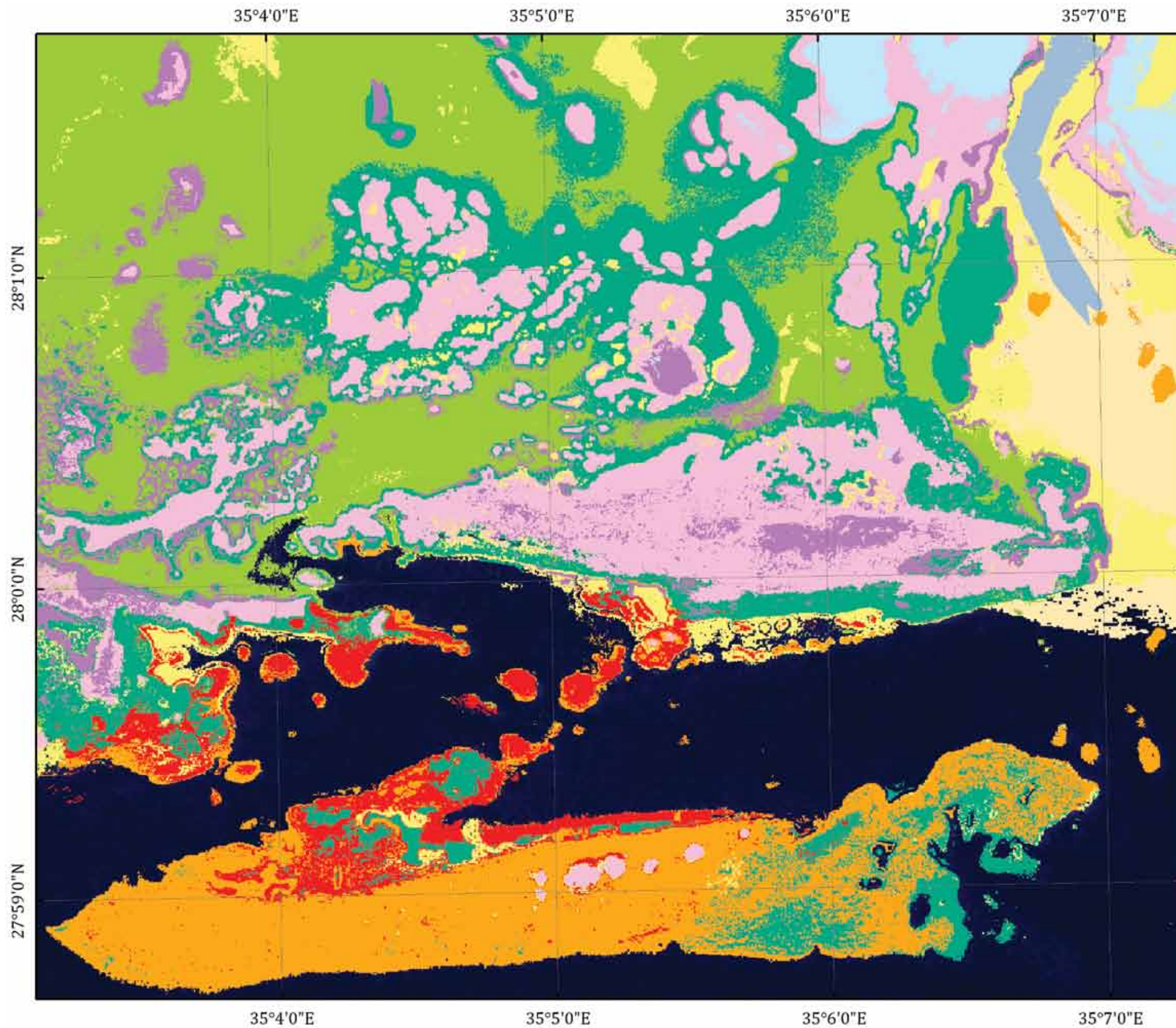
### Ras Al-Qasabah Habitats

- Windward coral crests
- Leeward coral crests
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- Scoured channels
- Carbonate hardground and reef flats
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- Deep lagoonal sands
- Sand and mud flats
- Deep water

1:24,000







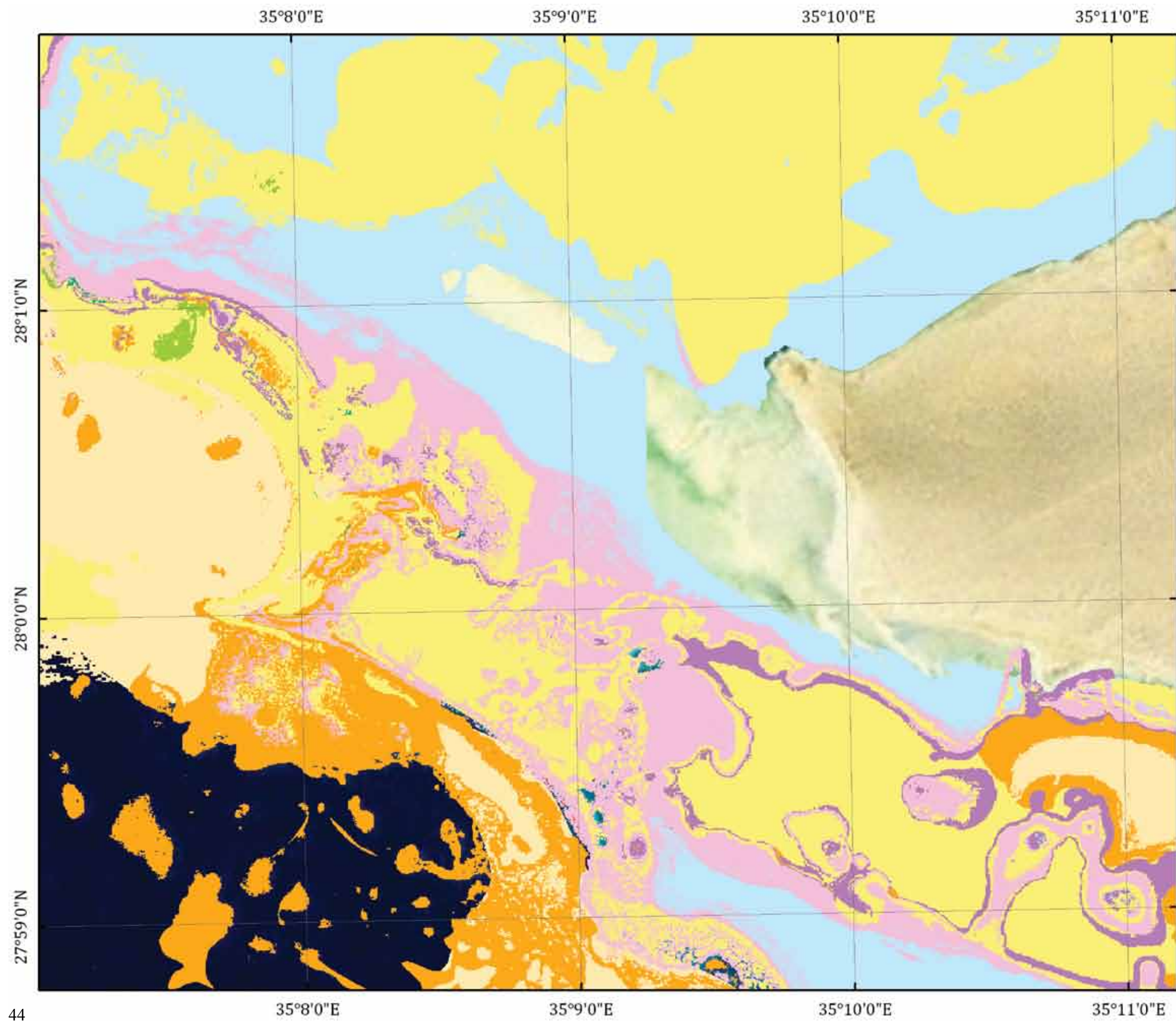
### Ras Al-Qasabah Habitats

- Windward coral crests
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- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water



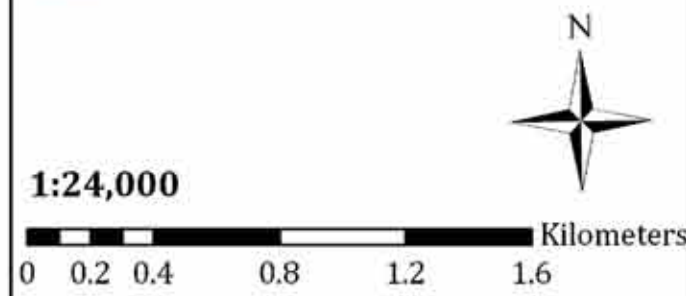
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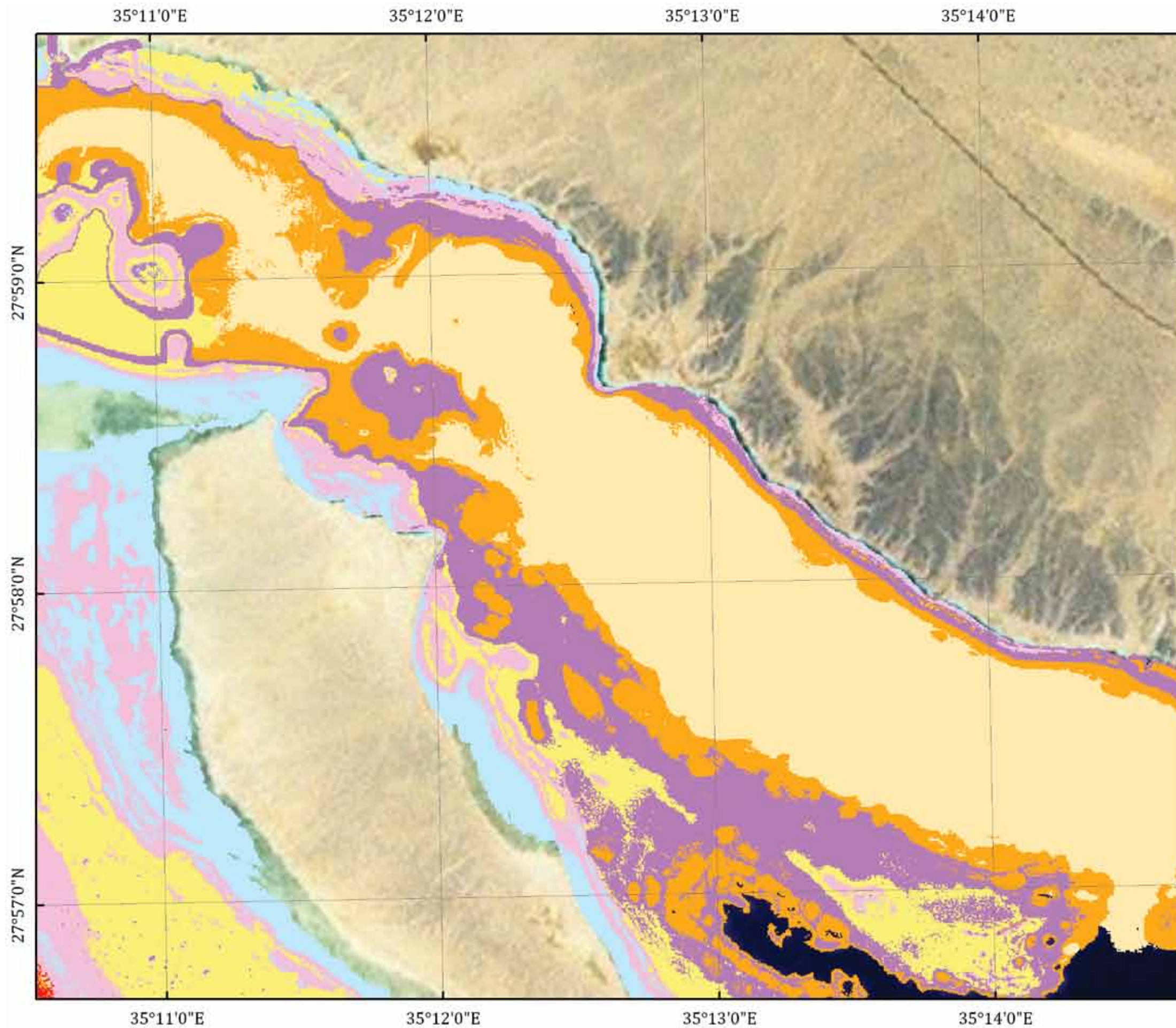




**Ras Al-Qasabah Habitats**

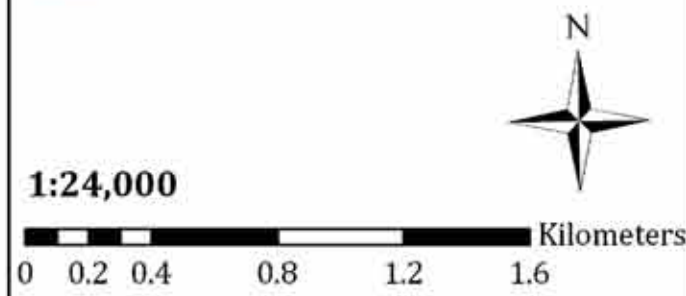
- Windward coral crests
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- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

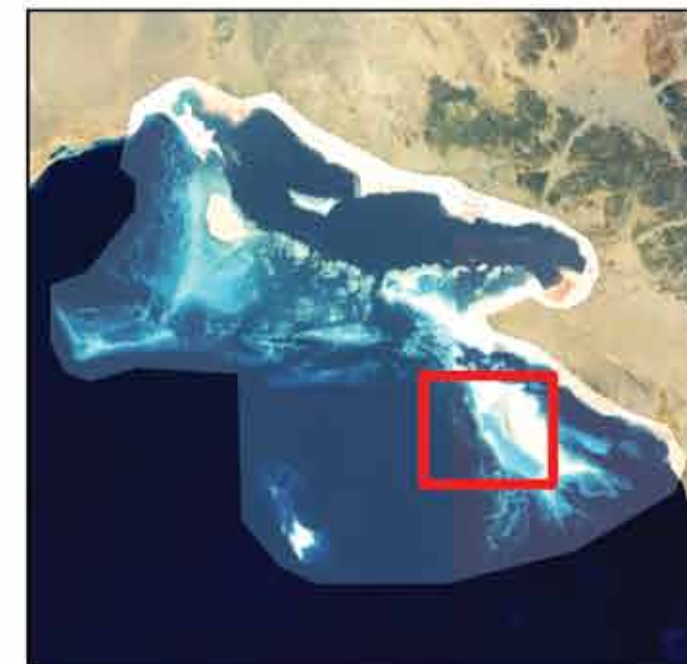
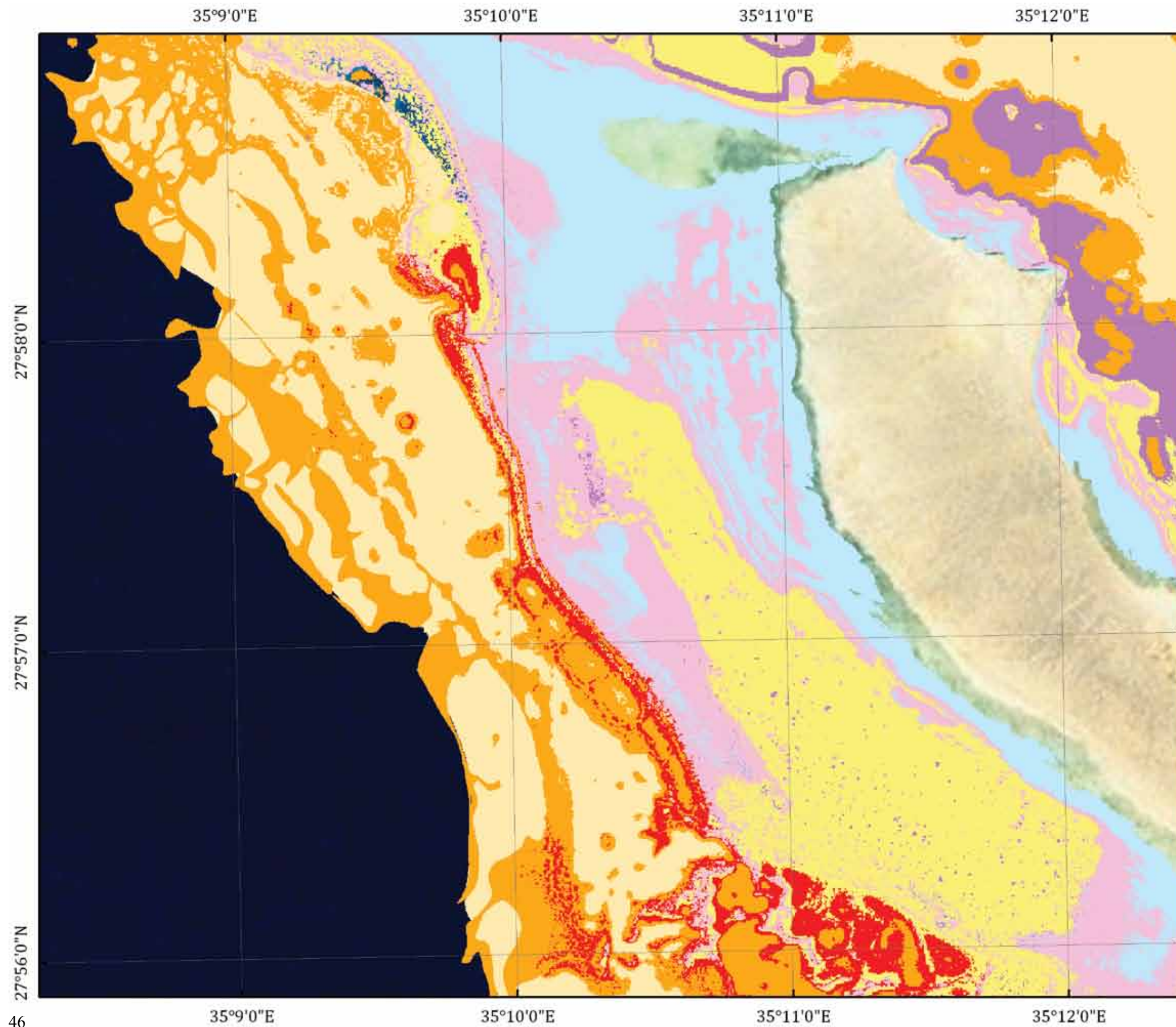




**Ras Al-Qasabah Habitats**

- Windward coral crests
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- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water





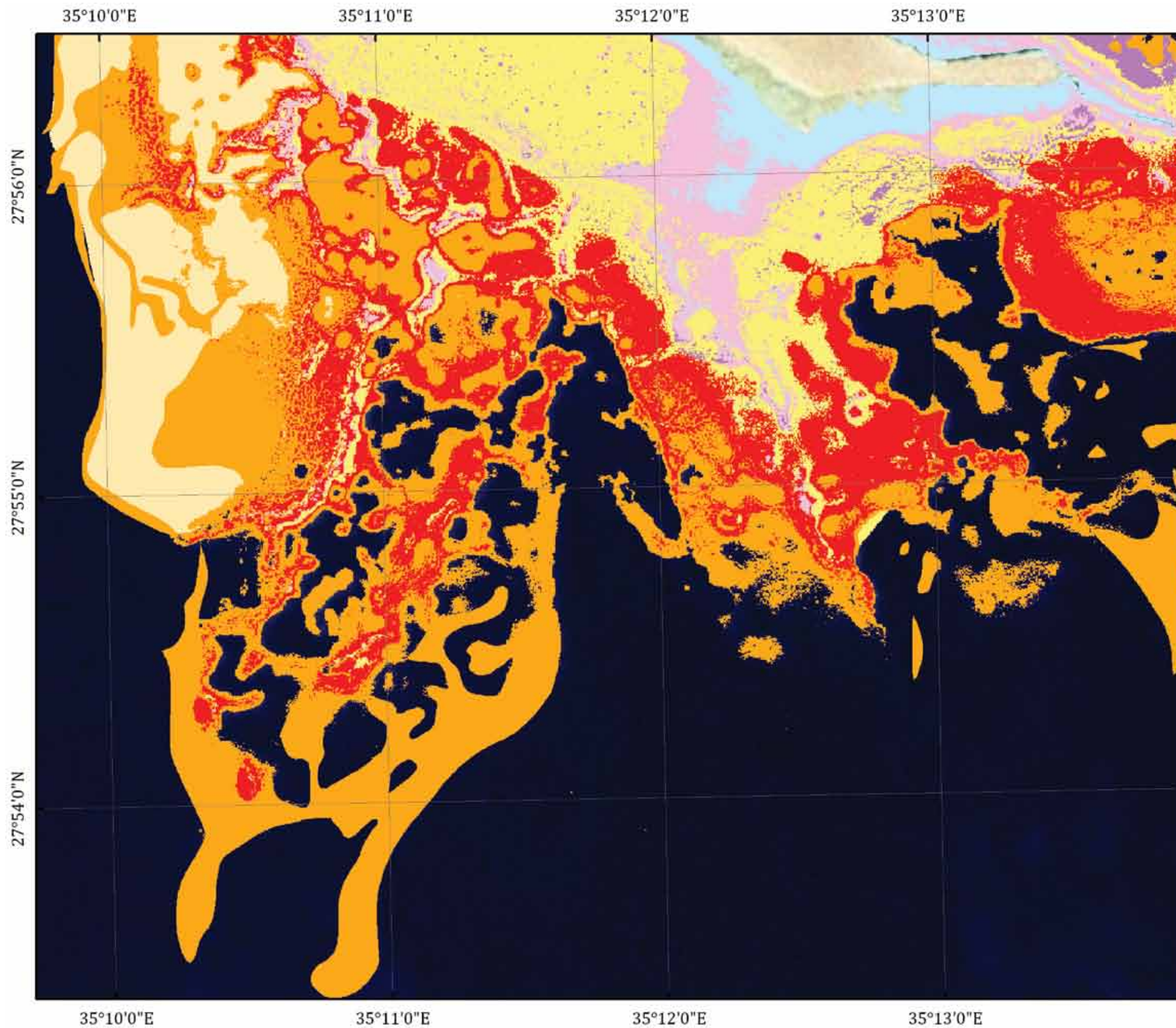
### Ras Al-Qasabah Habitats

- Windward coral crests
- Leeward coral crests
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- Scoured channels
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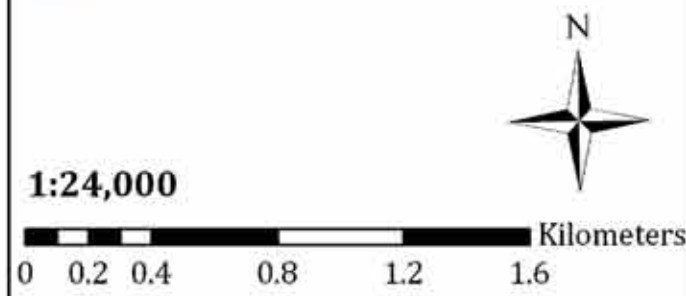
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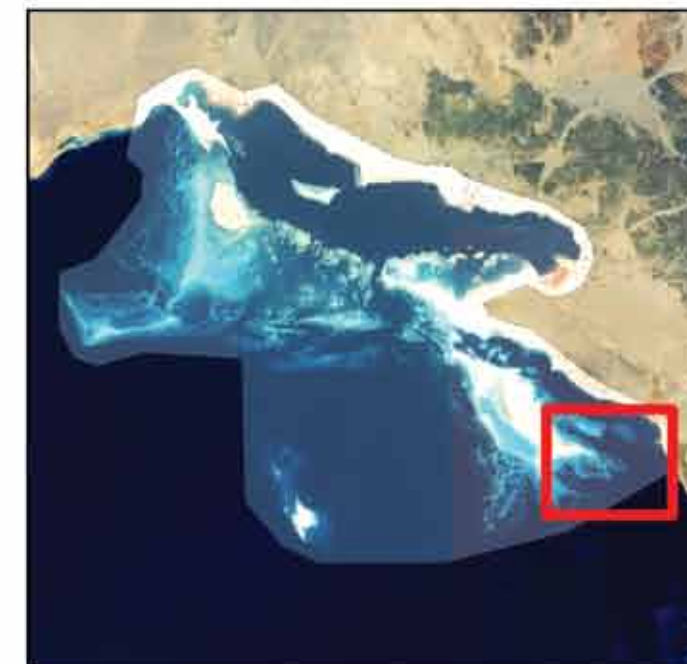
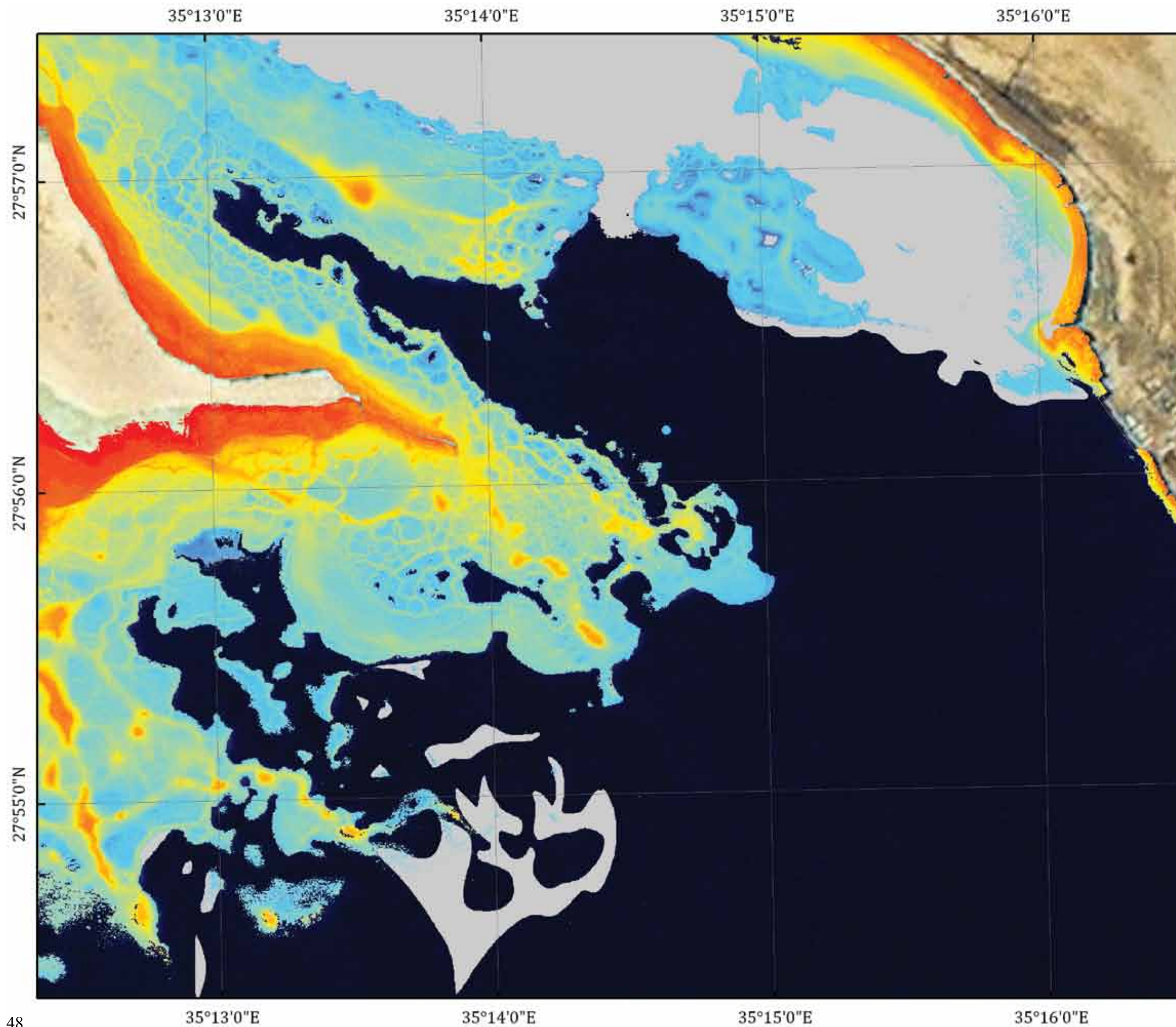


**Ras Al-Qasabah Habitats**

- Windward coral crests
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- Deep lagoonal sands
- Sand and mud flats
- Deep water







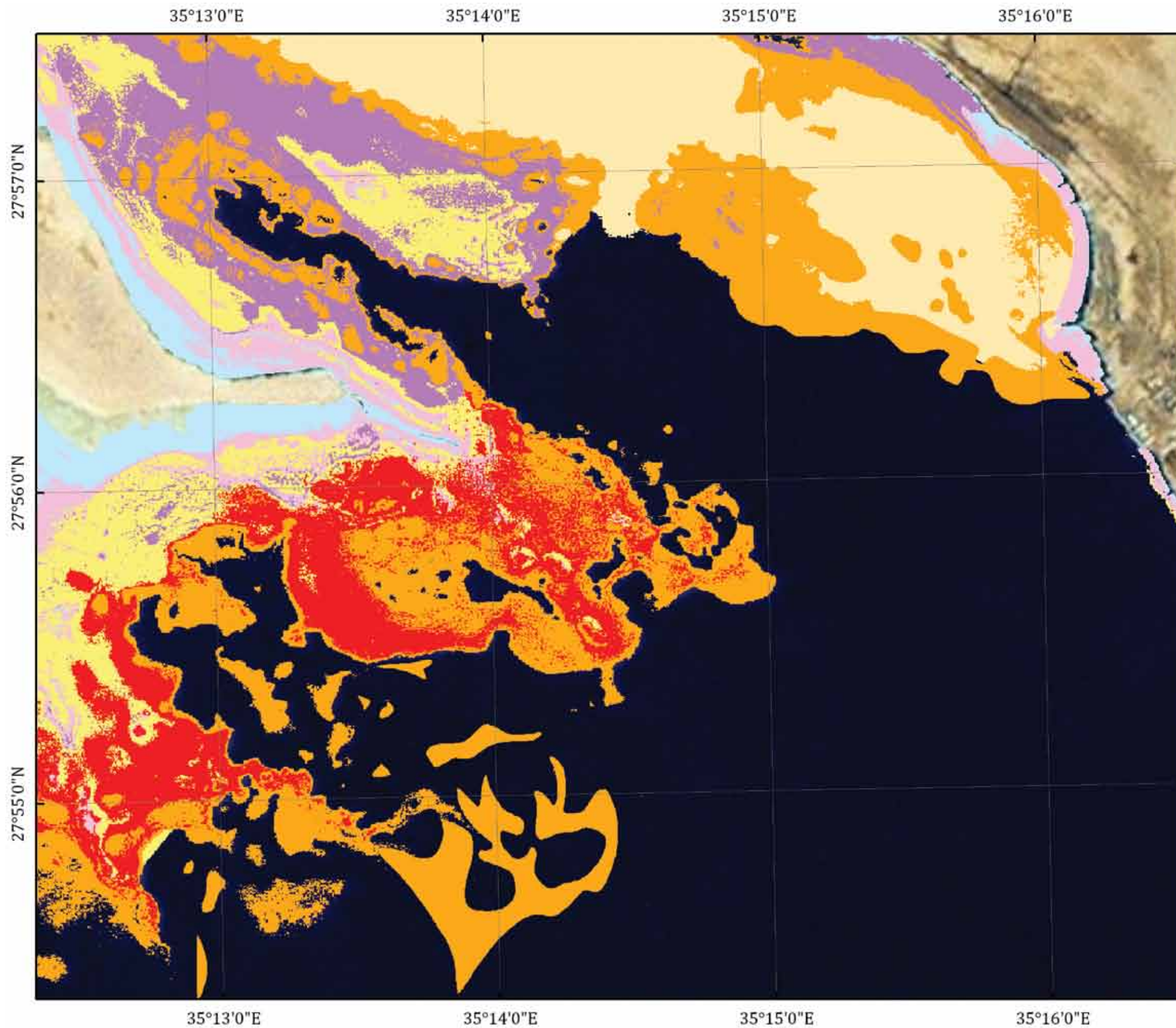
**Ras Al-Qasabah Bathymetry**

Depth, meters

0 - 0.9	12 - 12.9
1 - 1.9	13 - 13.9
2 - 2.9	14 - 14.9
3 - 3.9	15 - 15.9
4 - 4.9	16 - 16.9
5 - 5.9	17 - 17.9
6 - 6.9	18 - 18.9
7 - 7.9	19 - 19.9
8 - 8.9	20 - 20.9
9 - 9.9	21 - 40
10 - 10.9	Deep water
11 - 11.9	

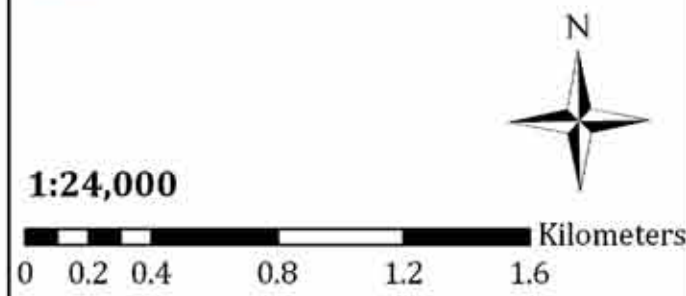
1:24,000





**Ras Al-Qasabah Habitats**

- Windward coral crests
- Leeward coral crests
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- Reef falls and drop-offs
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- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

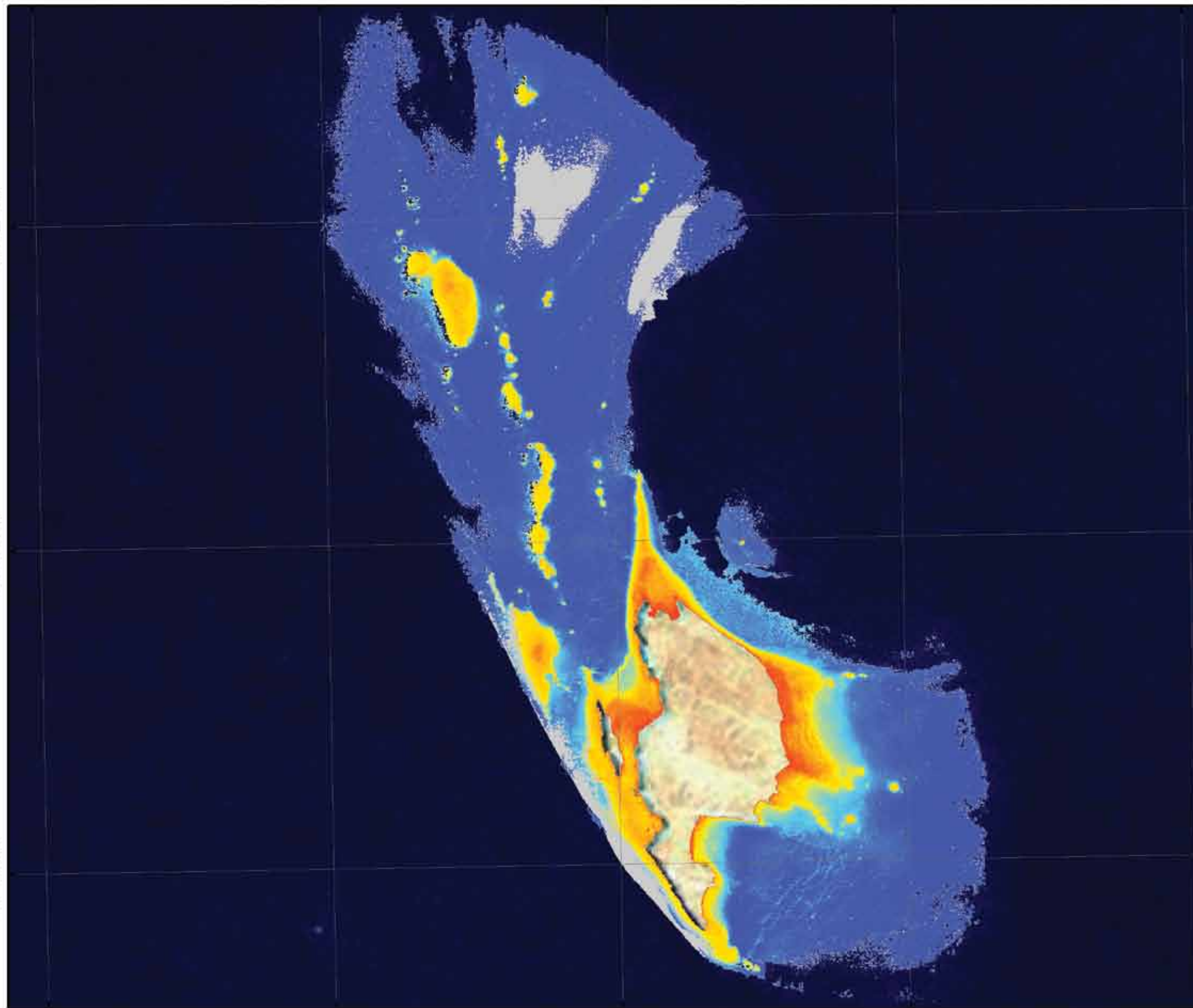


35°2'0"E 35°3'0"E 35°4'0"E 35°5'0"E 35°6'0"E

27°56'0"N

27°55'0"N

27°54'0"N



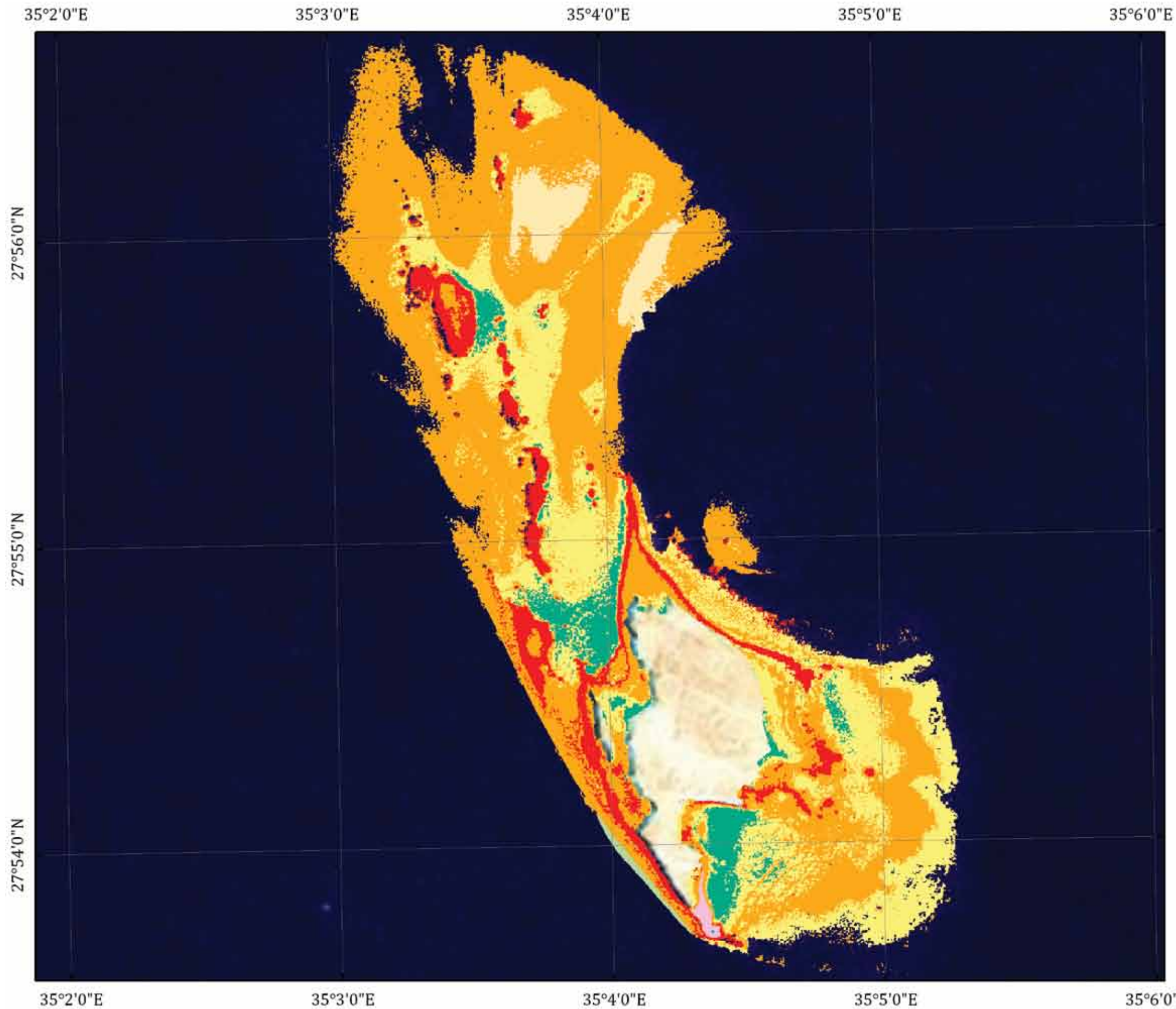
### Ras Al-Qasabah Bathymetry

Depth, meters

0 - 0.9	12 - 12.9
1 - 1.9	13 - 13.9
2 - 2.9	14 - 14.9
3 - 3.9	15 - 15.9
4 - 4.9	16 - 16.9
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6 - 6.9	18 - 18.9
7 - 7.9	19 - 19.9
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9 - 9.9	21 - 40
10 - 10.9	Deep water
11 - 11.9	

1:24,000





### Ras Al-Qasabah Habitats

- Windward coral crests
- Leeward coral crests
- Columnar frameworks
- Reef falls and drop-offs
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- Seagrass meadows
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- Shallow sand sheets
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- Sand and mud flats
- Deep water

1:24,000





*Al Wajh Bank*





Salt tolerant bushes located close to the water's edge on Birrim Island.



*Avicennia marina* mangroves on the leeward side of Qad Az Zawraq inside Al Wajh barrier reef.

Opposite page, left: Location of Al Wajh Bank. Source of basemap: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

Opposite page, top right: Aerial photograph of the coastline, nearshore islands, and shallow reef habitat on the southern end of Al Wajh Bank.

Opposite page, bottom right: Aerial image of a small island within Al Wajh. The perimeter of the island is colonized by coastal vegetation including mangroves at the northeastern tip. Shallow submerged sandy areas surround the island, with reef development fringing the edge, adjacent to deeper water.

## Al Wajh Bank

Al Wajh Bank (25°35'N, 36°45'E) is in the northeast part of the Red Sea in Tabuk, Saudi Arabia, between the towns of Al Wajh in the north and Umluj in the south. It encompasses an area of approximately 2,880 sq km, extending 26-50 km offshore from the mainland and running parallel to the shoreline for about 50 km before turning landward at its northern and southern ends.

Al Wajh Bank is comprised of mainland coastal habitats, a central lagoon with shallow grassbed, algal, and mangrove communities; complex reef systems; and a plethora of islands. The seaward (western) side of the bank is enclosed by an extensive barrier reef, which drops abruptly to depths of 500 m or more on its seaward edge. Numerous islands and associated reef formations are supported on the shelf inside the barrier reef; several islands are also located offshore between Al Wajh and Um Luj, and others form a major component of the barrier reef system. The mainland coast is characterized by alluvial sand flats with several saltmarsh communities found on the saline sandy flats near the shoreline and a number of wide wadis drainage systems. The central lagoon covers an area of about 1,400 sq km, with a maximum depth of 30-40 m and becoming progressively shallower toward land. The southern part of the bank is shallower than the northern part and contains extensive seagrass beds and tidal flats. The lagoon is flushed by several narrow (< 200 m wide) channels that connect the inside and outside of the bank. Although tidal amplitude is usually minimal (< 1m), the narrowness of the openings between the bank and the open ocean generates strong currents.

The archipelago contains six main islands and over 40 smaller islands, ranging in size from 0.01 sq km to 11 sq km. Most islands are sandy and flat, whereas others are rocky with low cliffs, usually of less than 5 m height. The protected sides of the islands often have mangrove communities, grassbeds, and shallow subtidal and intertidal sand and mud flats. The three main islands located on the outer barrier reef are Jazirat Umm Rumah, Jazirat Birrim, and Jazirat Shaybarah. Qummaan, the largest island within the lagoon, is a relatively flat, sandy island surrounded by a shallow fringing reef. South of Qummaan, and closer to shore, are numerous other large, sandy islands, including Shurayrat, Suwayhil, and Abu Lahiq. Islands within the lagoon to the north of Qummaan are small and low-lying. Ash Shaykh Marbat is a steep rocky island that bounds the northern end of the Bank.

Some islands in the region support vegetation, consisting predominantly of mangroves and salt-tolerant bushes, but elsewhere they are barren. *Avicennia marina* mangrove thickets occur along the coastline, and both *A. marina* and *Rhizophora mucronata* are found on islands on the outer barrier reef. Relatively dense mangrove stands are found at Hanak and nearby islands between latitudes 25° and 26° N, while the largest stands of *R. mucronata* stands occur around Umm Rumah Island and on the mainland shore at Dugm Sabq. The mainland coast adjacent to the Bank consists predominantly of an alluvial sand plain interspersed with small wadis. At the northern and southern end of the Bank, the wadis extend into coastal sharms with extensive reef development on their outer margins.



Coastal vegetation on Jazirat Birrim. An uplifted fossil reef is visible in the background.



Small sandy island near Umm Rumah colonized by mangroves.



Beachrock on Ghawwar, an offshore island adjacent to the barrier reef.

The Al Wajh region contains the most extensive coral reef system in the Red Sea and the only barrier reef system. The Bank and adjacent coastline to the north and south support a great range of reef types, including reefs developed in open and closed sharms, mainland and island fringing reefs, platform reefs, reticulate reef systems, submerged patch reefs, lagoon pinnacles, and a well-developed barrier reef. Two deeper submerged ribbon reef systems also lie outside the bank, due south. The outer edge of the barrier reef lies 15-25 km offshore, running parallel to the shoreline for about 50 km, before changing course landward at its southern and northern end. In several locations, the barrier reef system contains a wide reef flat, exceeding 50 m. The southern part of Al Wajh Bank is shallower than the northern part. A large platform between 10-15 m deep in the northern lagoon supports extensive seagrass beds, tidal flats and mangroves. The reef systems rest upon ancient alluvial plains, having developed in conjunction with Holocene sealevel rise over the last 6,000 years. The quaternary coastal plain abutting the reef areas is wider than elsewhere along the northcentral coast. Horst-and-graben faulting was an important structuring process for the region.



Reef scenes at Al Wajh Bank.

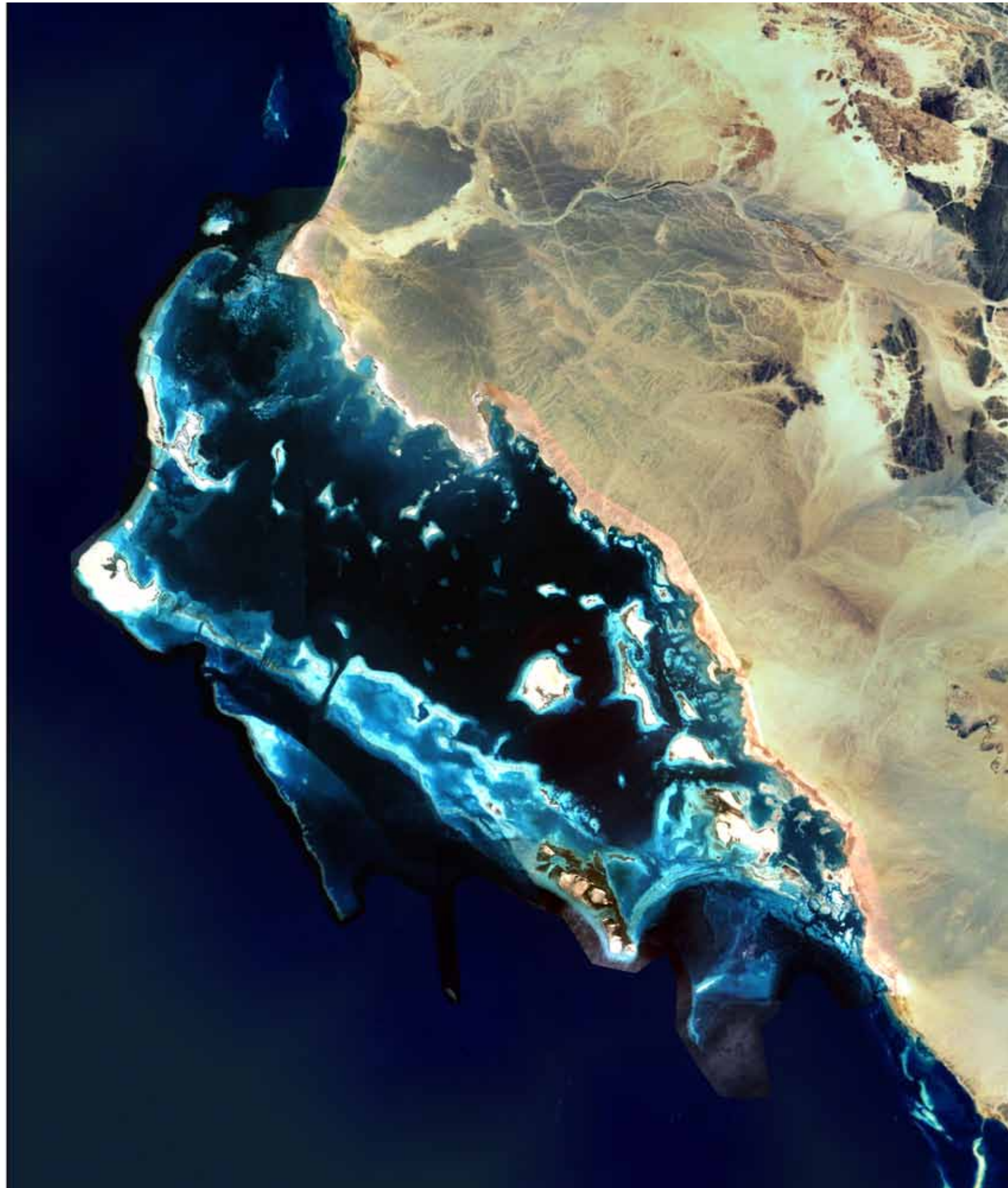
Left: *Acropora* thicket on the barrier reef, at 6 m depth.

Top center: Small coral pinnacle with table acroporids; leeward reef, at 10 m depth.

Bottom center: Reef flat community on the barrier reef, at 3 m depth.

Top right: Mixed coral assemblage on the fore reef at the southern end of Al Wajh, at 5 m depth. A large massive *Porites* colony in the center is surrounded by smaller branching, massive, and plating corals, including *Pocillopora*, *Acropora*, *Montipora*, *Millepora*, *Pavona*, *Favites*, and *Echinopora*.

Bottom right: Massive colony of *Porites lutea*, the dominant framework coral in the region. Diver is holding a 1-meter bar, at 6 m depth.



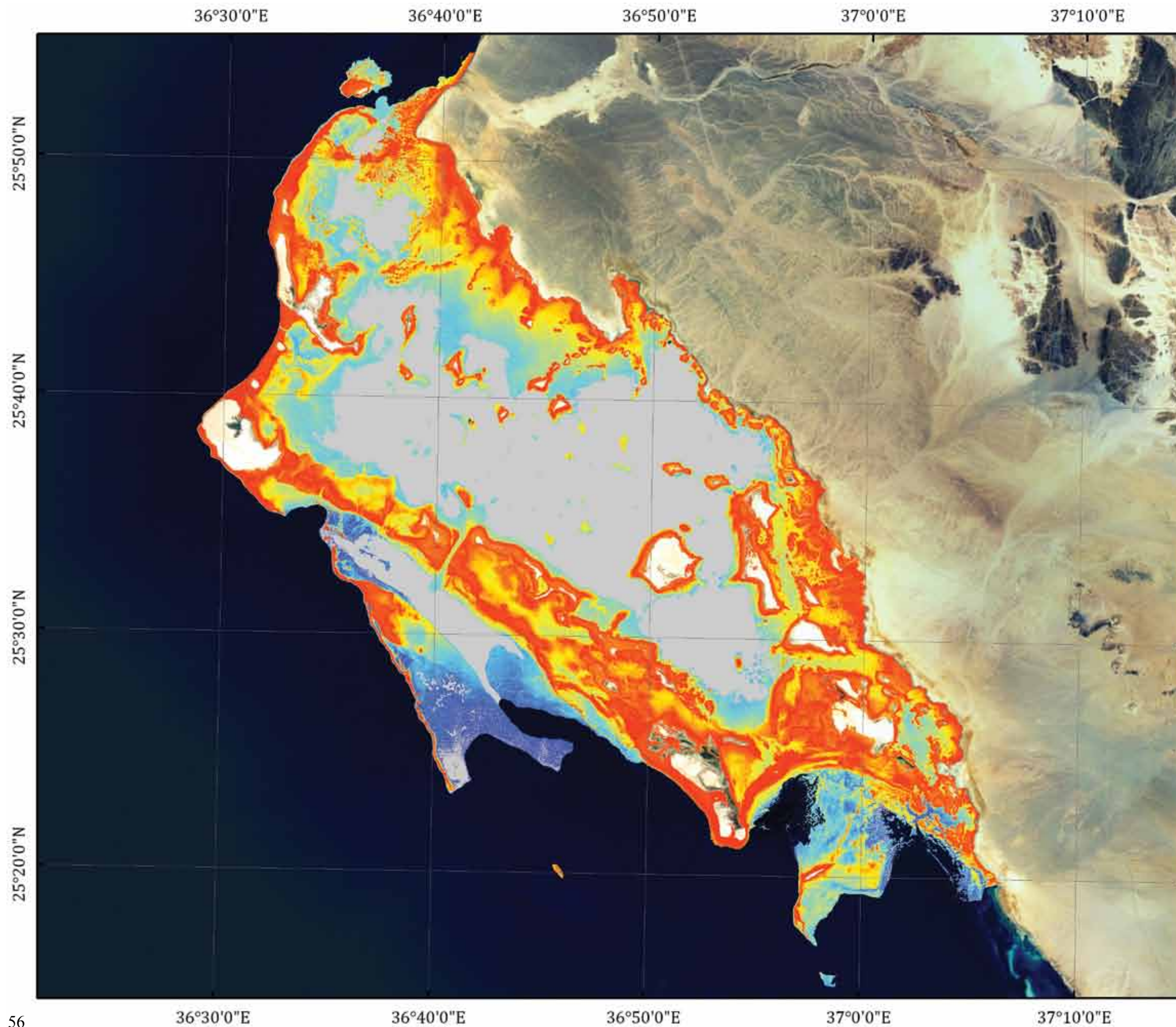
## Al Wajh Bank Imagery and Habitat Maps

Satellite imagery, bathymetry, and habitat maps for Al Wajh are illustrated on pages 55-95. QuickBird multispectral satellite imagery of Al Wajh (left), bathymetry (page 56), and a resulting habitat map for the same area (page 57) are shown at a scale of 1:315,000. A locator map and a habitat map are shown for the northern region (pages 58-59) and southern region (pages 74-75) at a scale of 1:180,000. Each regional map is followed by higher resolution habitat maps (1:24,000) and bathymetric maps for representative areas within Al Wajh and are on subsequent pages. Each of the six 1:24,000 scale bathymetric maps included in this section is on the left (even-numbered) page and the habitat map for the same area is shown on the right (odd-numbered) page. Habitat maps start in the north and work progressively southward. These include habitats associated with the barrier reef, lagoonal environments, and nearshore habitats. Source of terrestrial basemap imagery used in all habitat maps and bathymetric maps is: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

A total of 1,719 sq km of shallow marine habitats were mapped and subdivided into 15 habitat classes with sites below 25 m depth (deepwater) depicted in dark blue. The most extensive habitat types were shallow sand sheets and deep lagoonal sands, which made up over 67% of all marine habitats. Corals were found in six habitat types, covering an area of about 310 sq km. Hardground areas constitute an additional 100 sq km of the Bank, while other soft bottom habitats with seagrass, algae, and cyanobacteria occupied 13 sq km. Nearshore areas included some coral habitats, with mangroves, shallow sand and mud flats, and algal areas covering about 130 sq km.

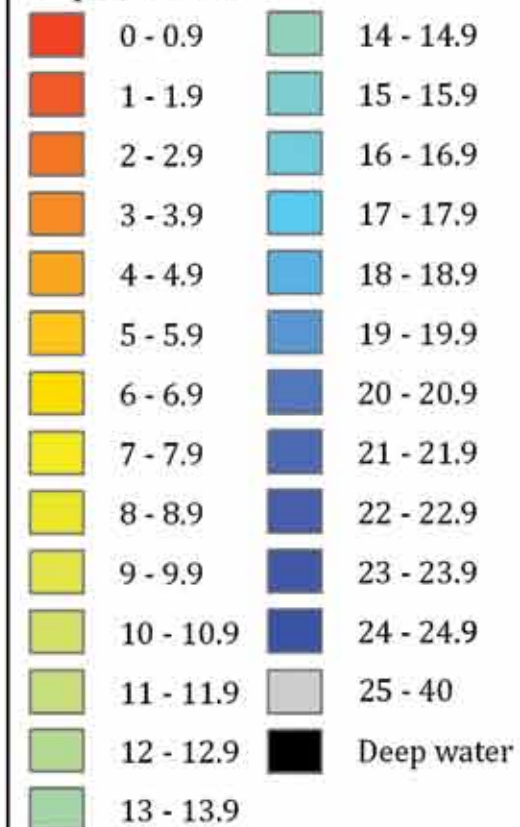
Al Wajh Habitats	Total area (sq km)	% region total
Reef walls and drop-offs	1.32	0.10
Windward coral crests	7.53	0.40
Leeward coral crests	51.88	3.00
Dense <i>Acropora</i> thickets	0.56	0.05
Columnar frameworks	62.97	3.70
Sparse corals, rubble, and sand	190.76	11.10
Seagrass meadows	7.03	0.40
Macroalgae, sponges, sandy hardgrounds	5.64	0.30
Cyanobacteria mats on sand	0.86	0.10
Mangroves and nearshore vegetation	13.34	0.80
Scoured channels	2.32	0.15
Carbonate hardground and reef flats	98.14	5.70
Shallow sand sheets	639.77	37.20
Deep lagoonal sands	521.74	30.40
Sand and mud flats	114.83	6.70
<b>TOTAL AREA MAPPED</b>	<b>1718.69</b>	<b>100</b>





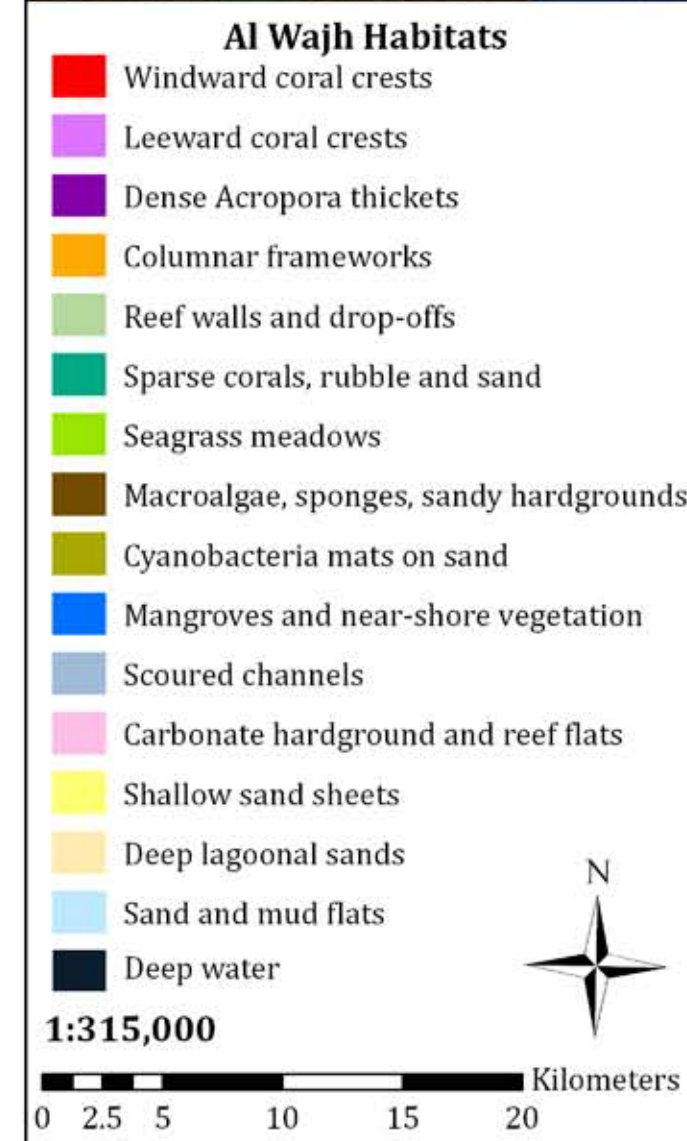
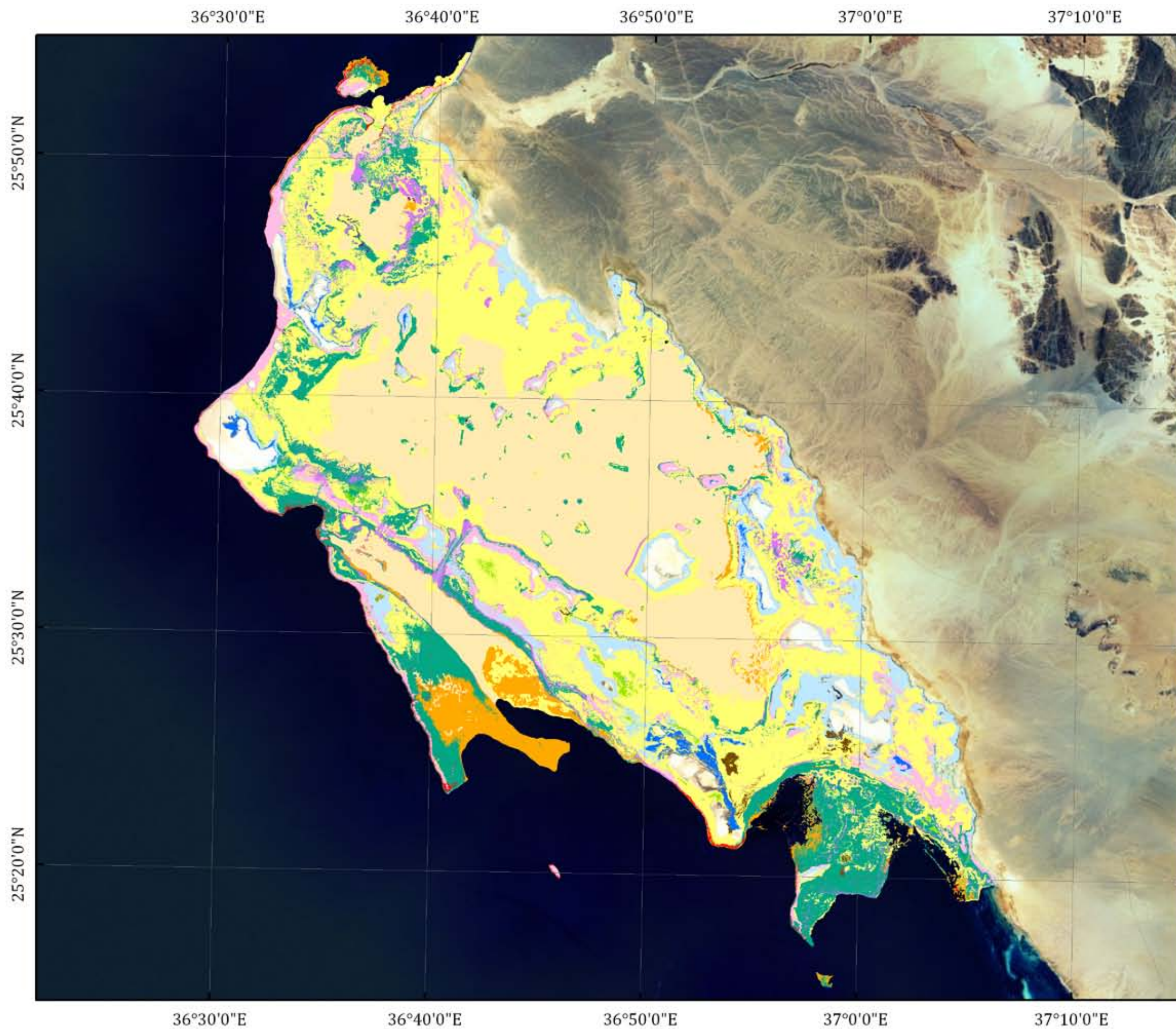
**Al Wajh Bathymetry**

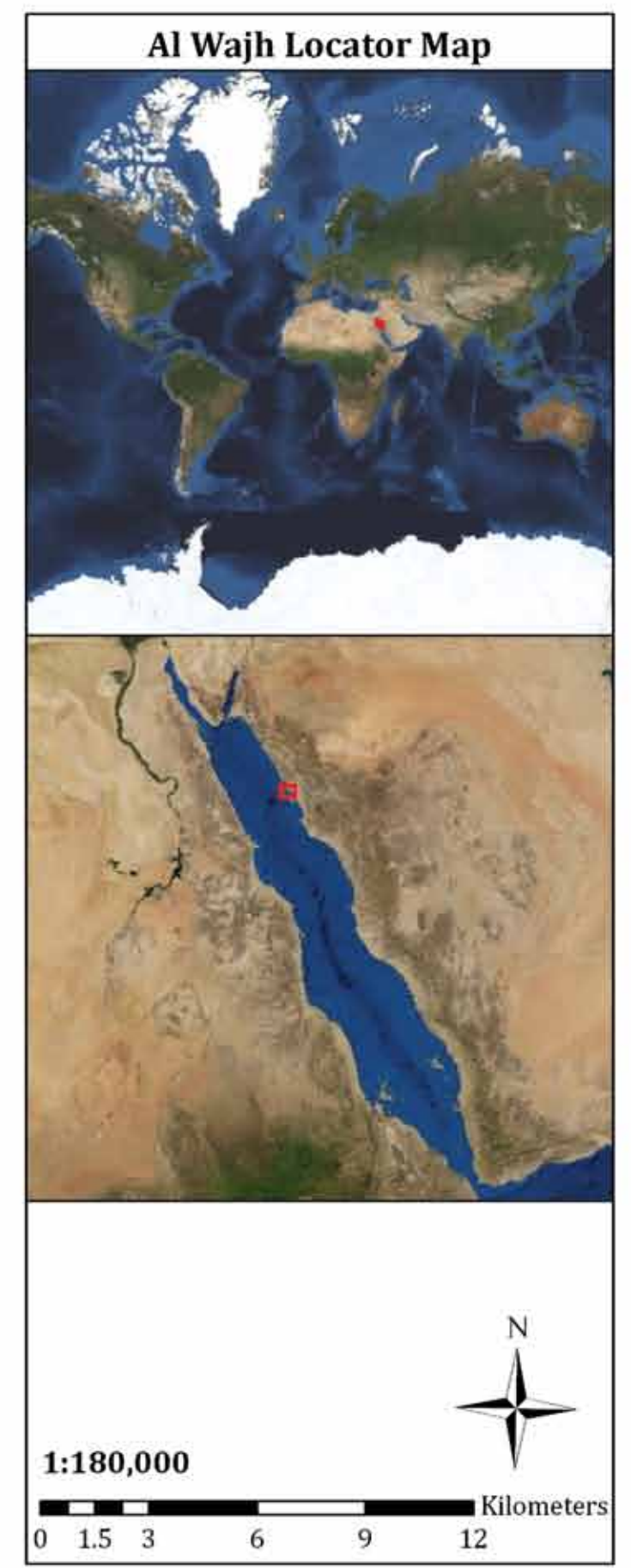
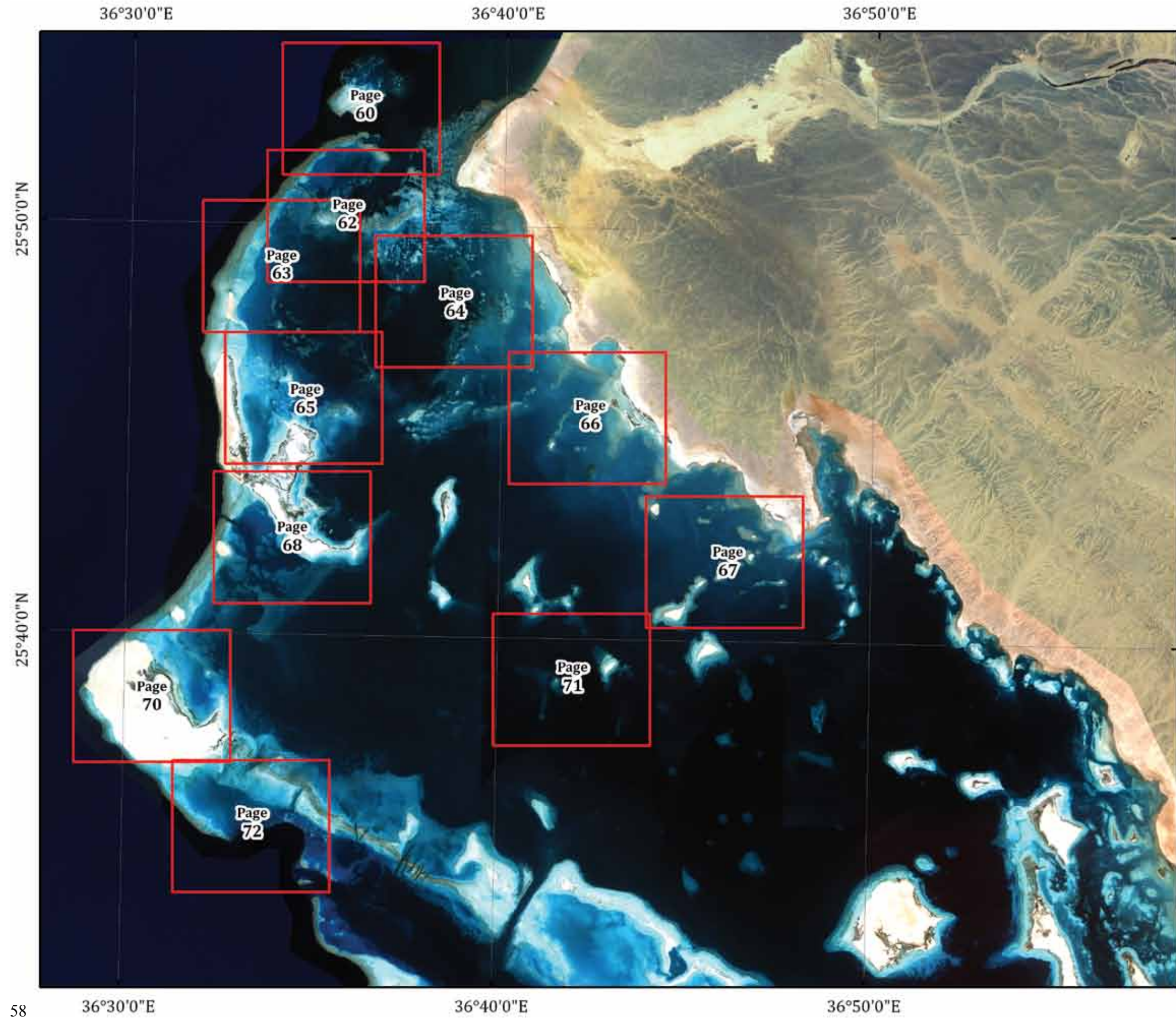
Depth, meters

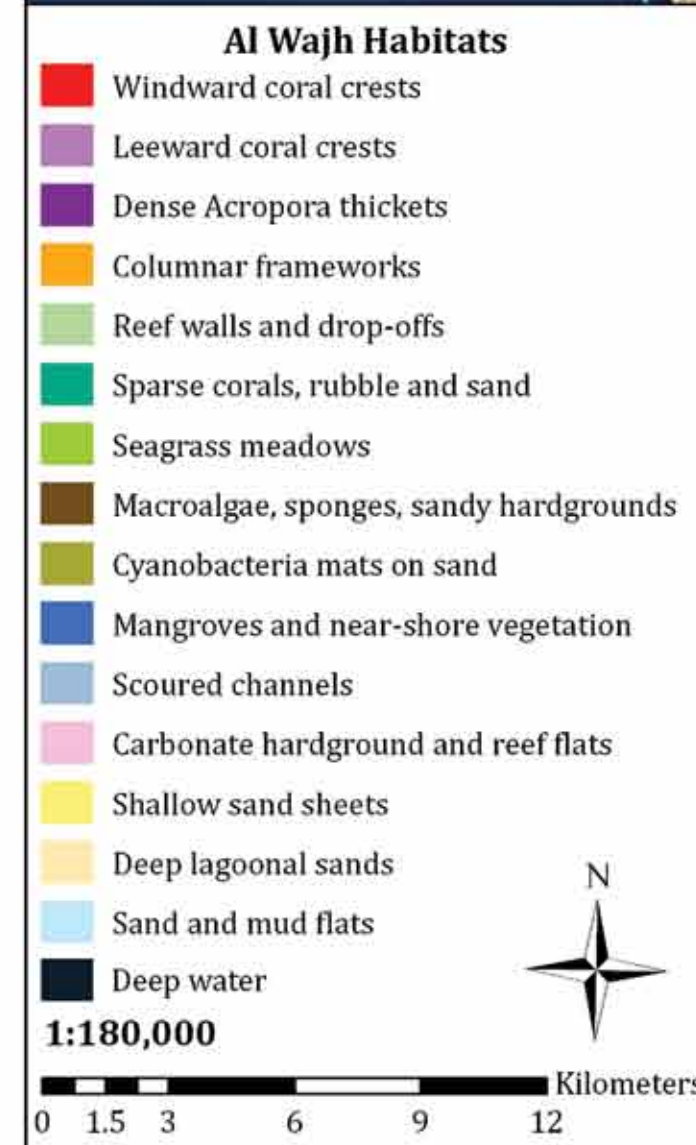
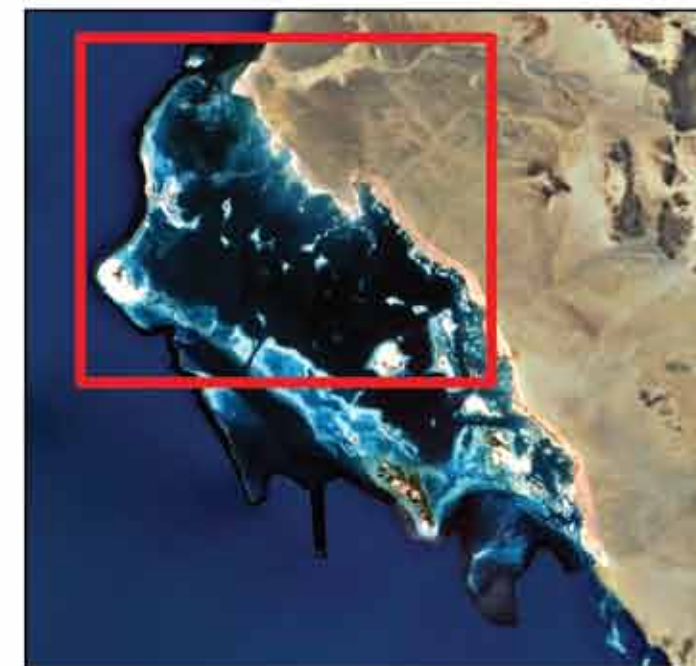
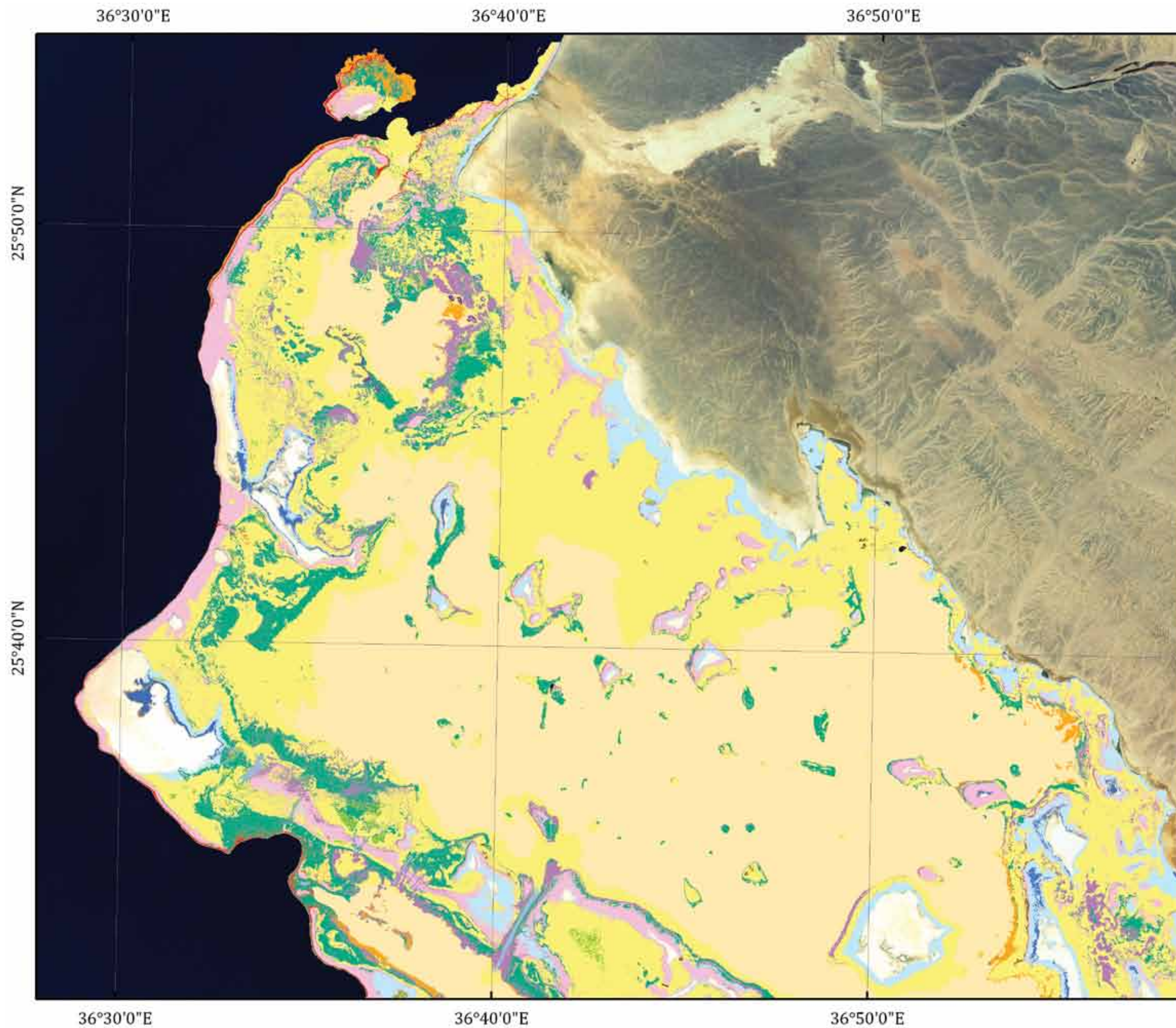


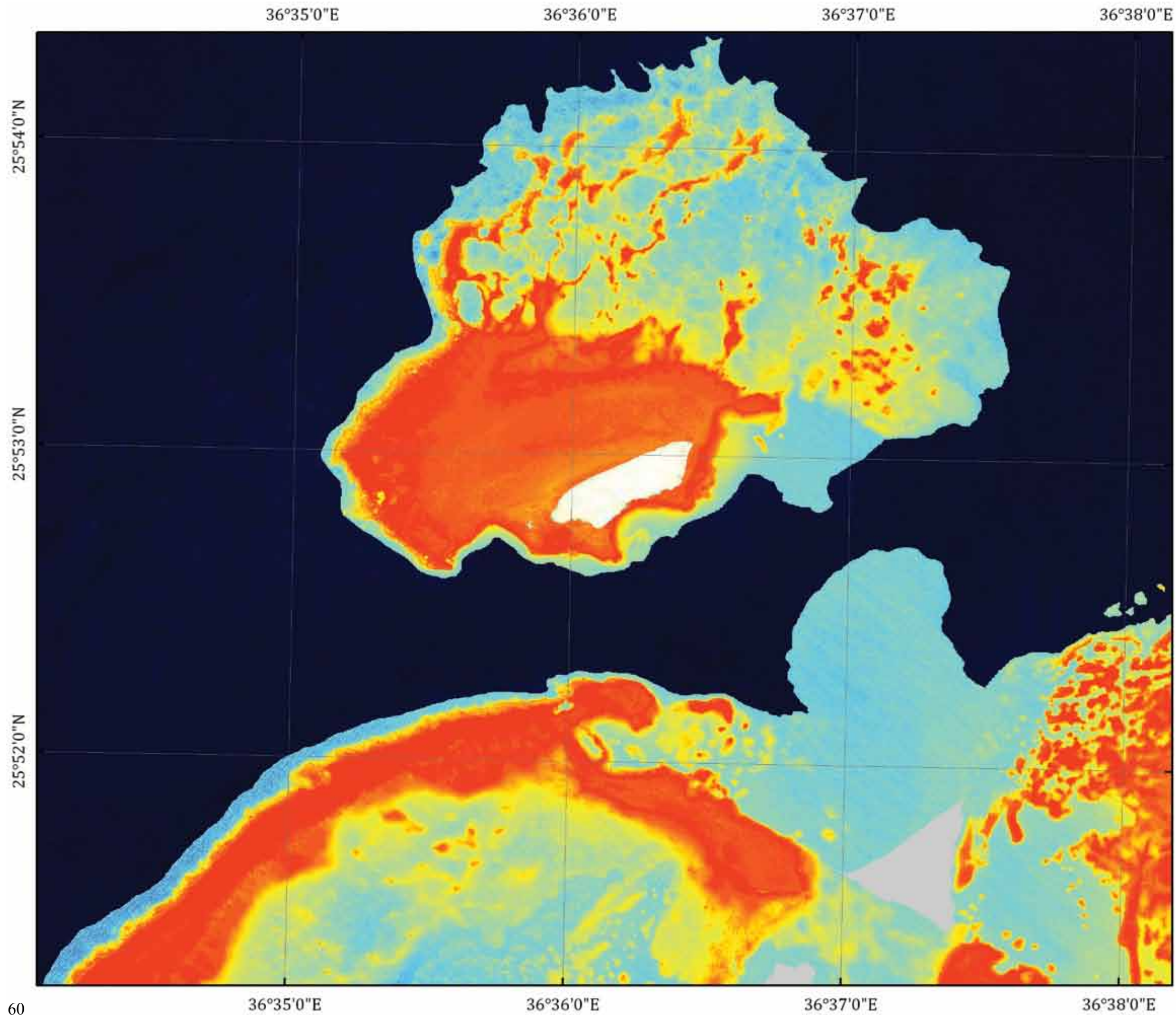
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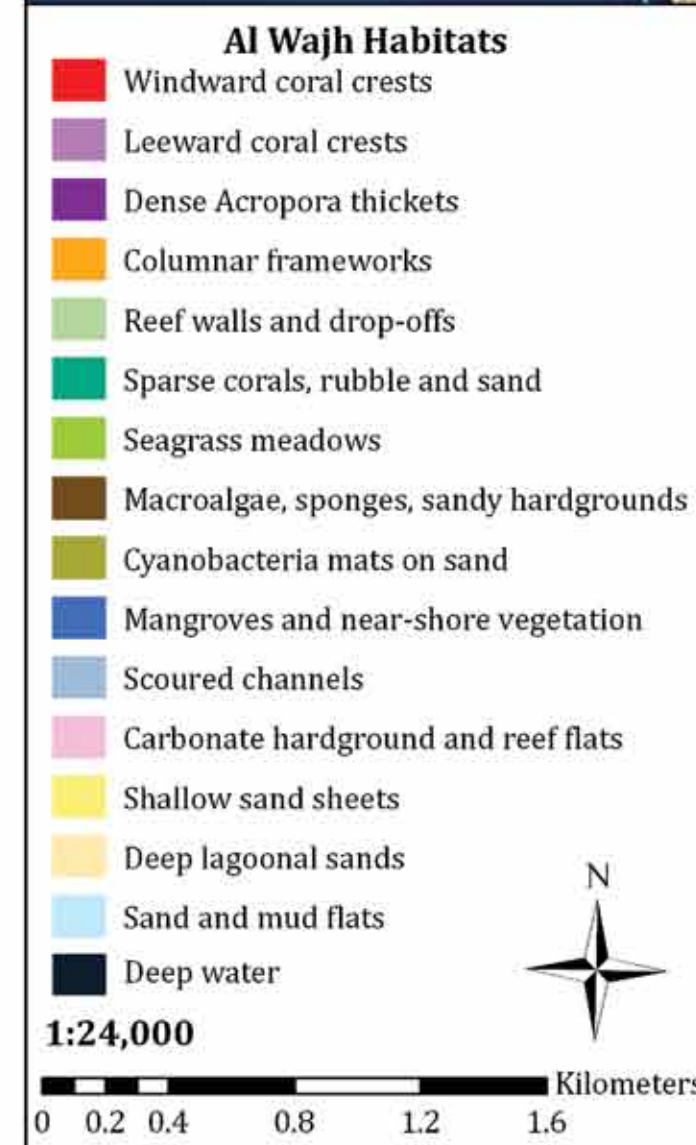
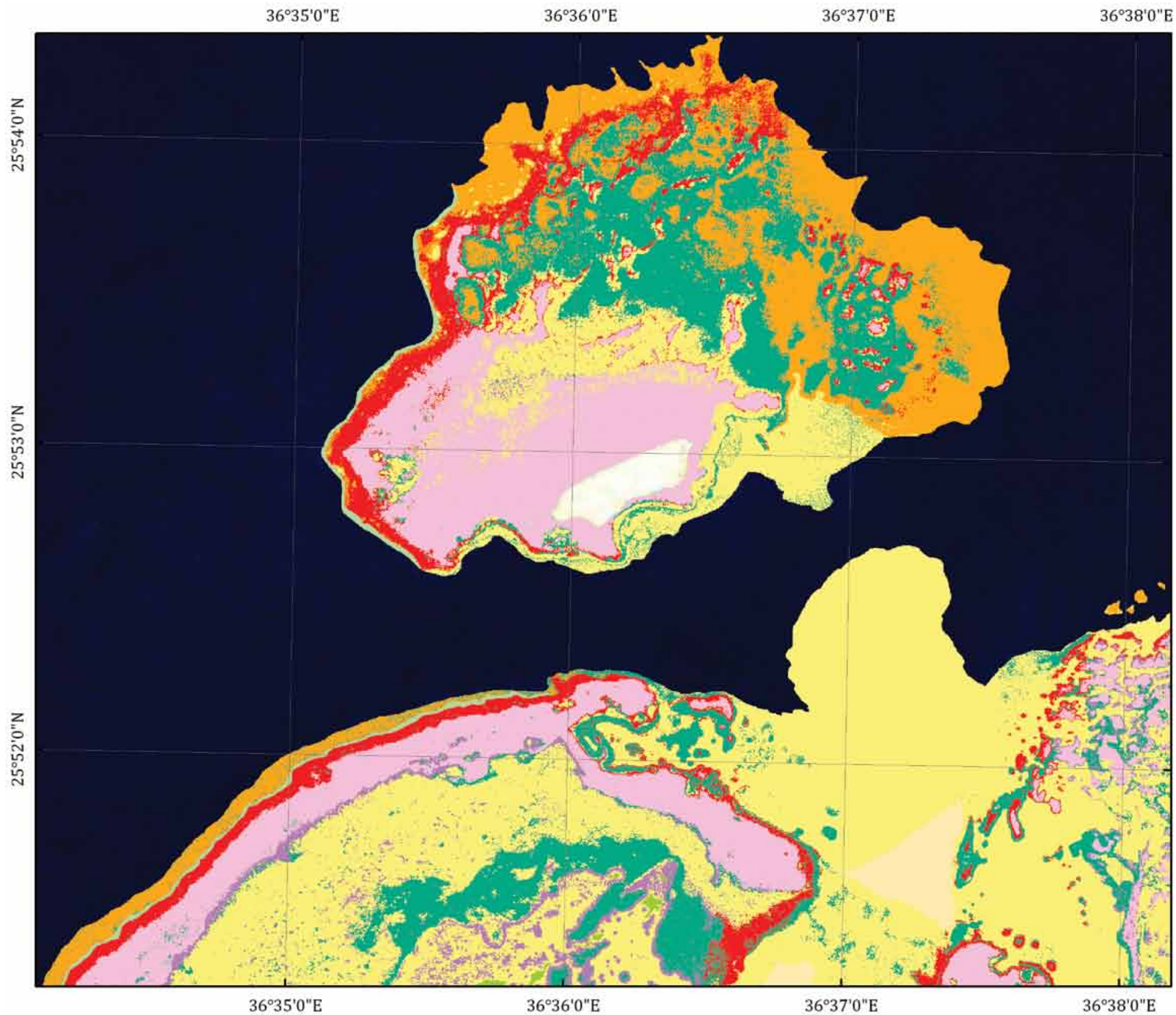
**Al Wajh Bathymetry**

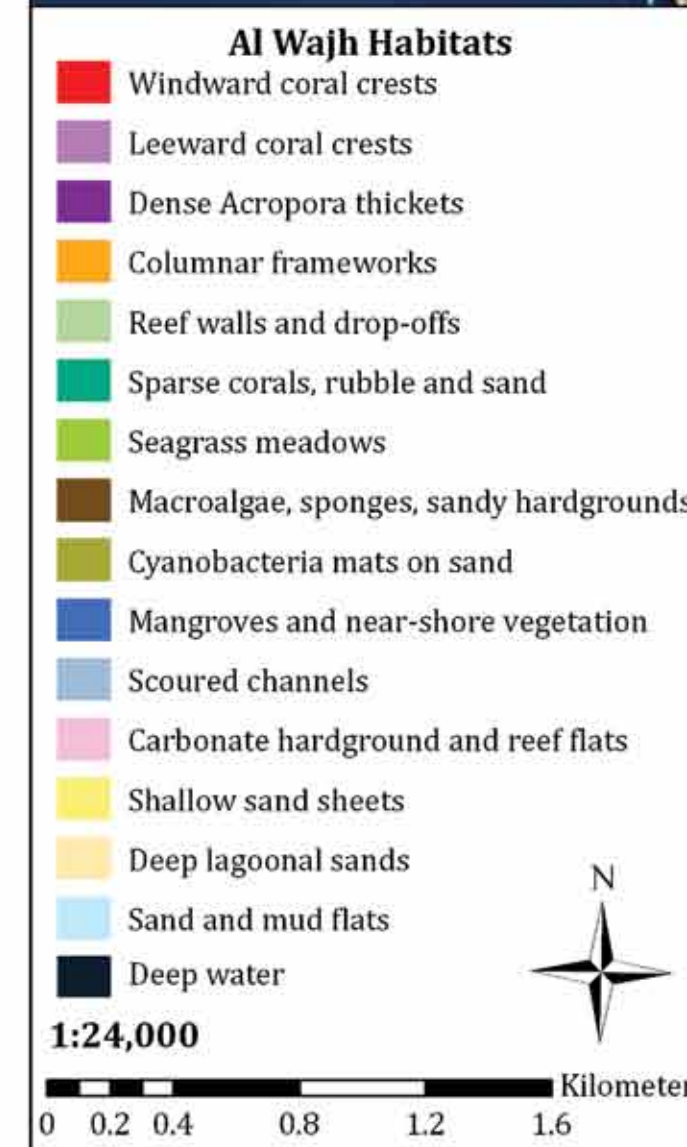
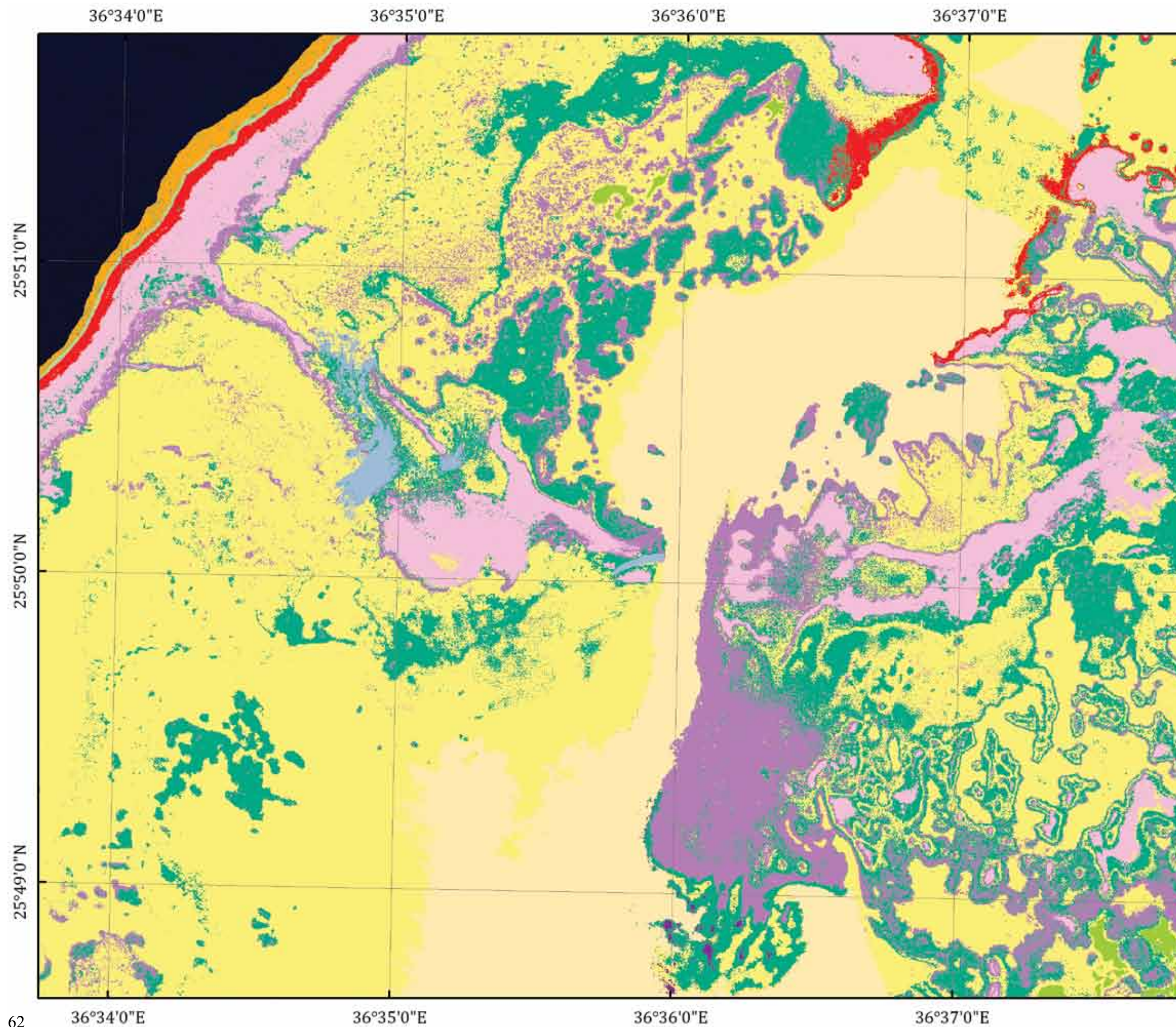
**Depth, meters**

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

**1:24,000**





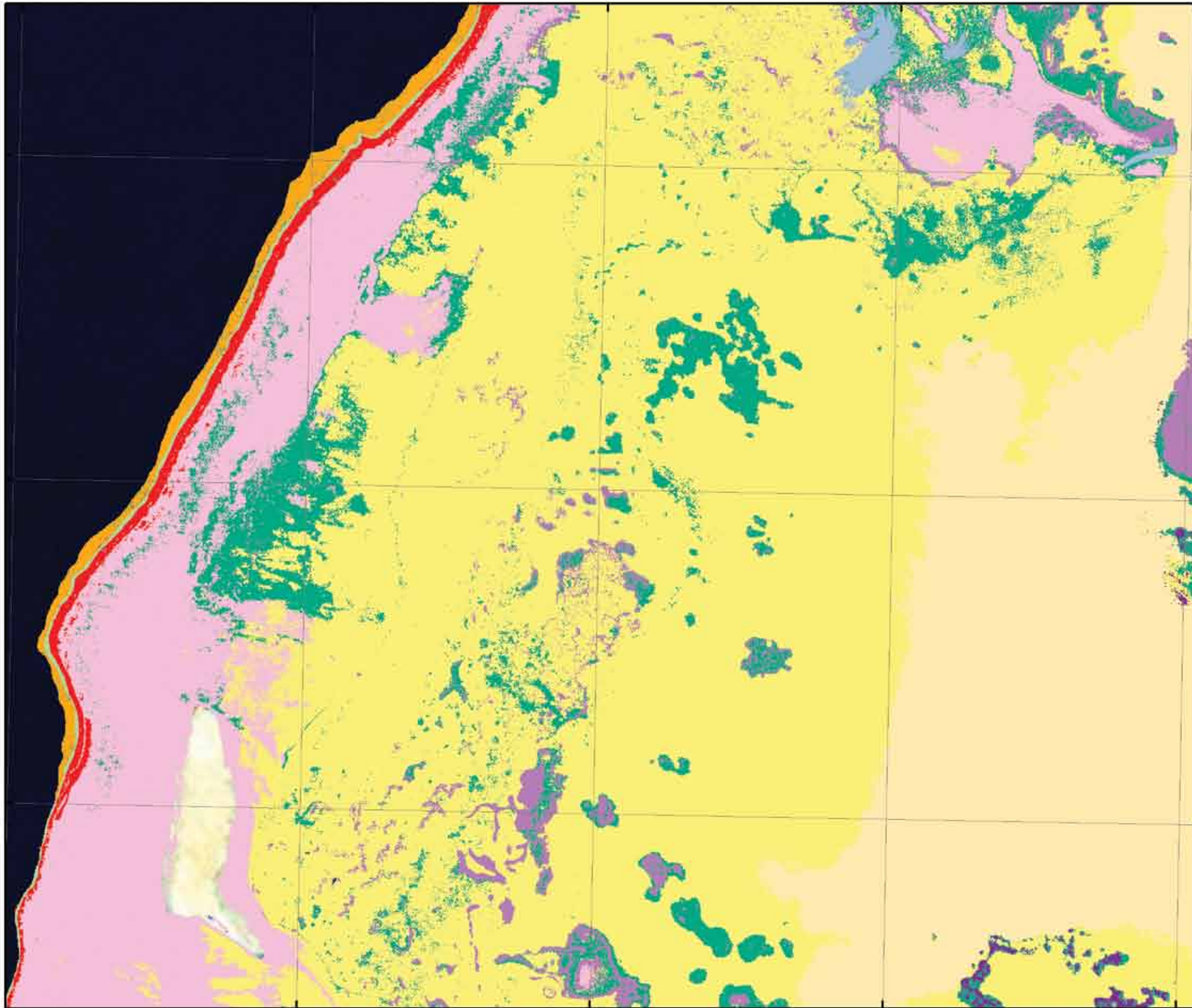


36°32'0"E      36°33'0"E      36°34'0"E      36°35'0"E      36°36'0"E

25°50'0"N

25°49'0"N

25°48'0"N



36°33'0"E      36°34'0"E      36°35'0"E      36°36'0"E



**Al Wajh Habitats**

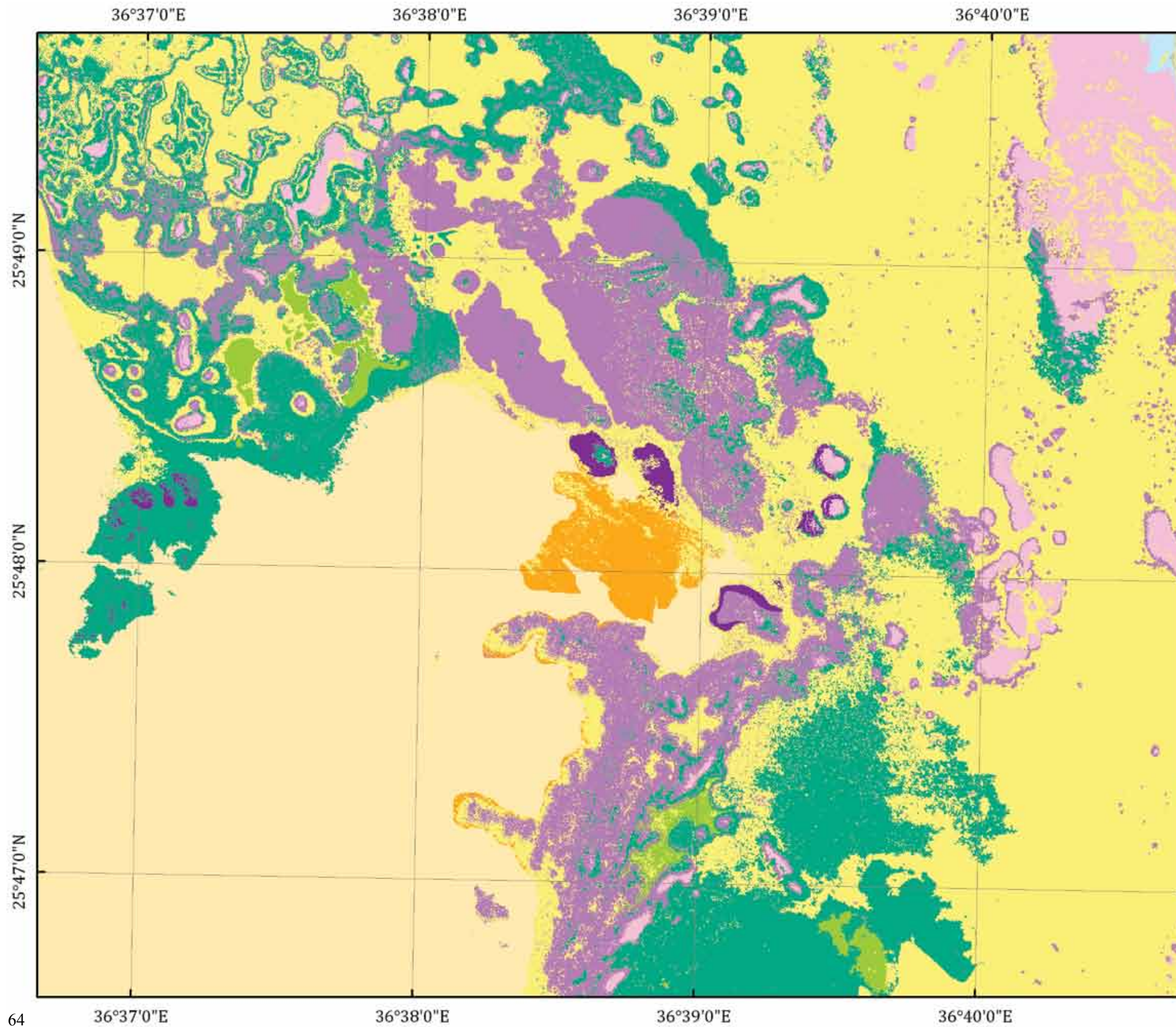
- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
- Macroalgae, sponges, sandy hardgrounds
- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

1:24,000

Kilometers

0 0.2 0.4 0.8 1.2 1.6



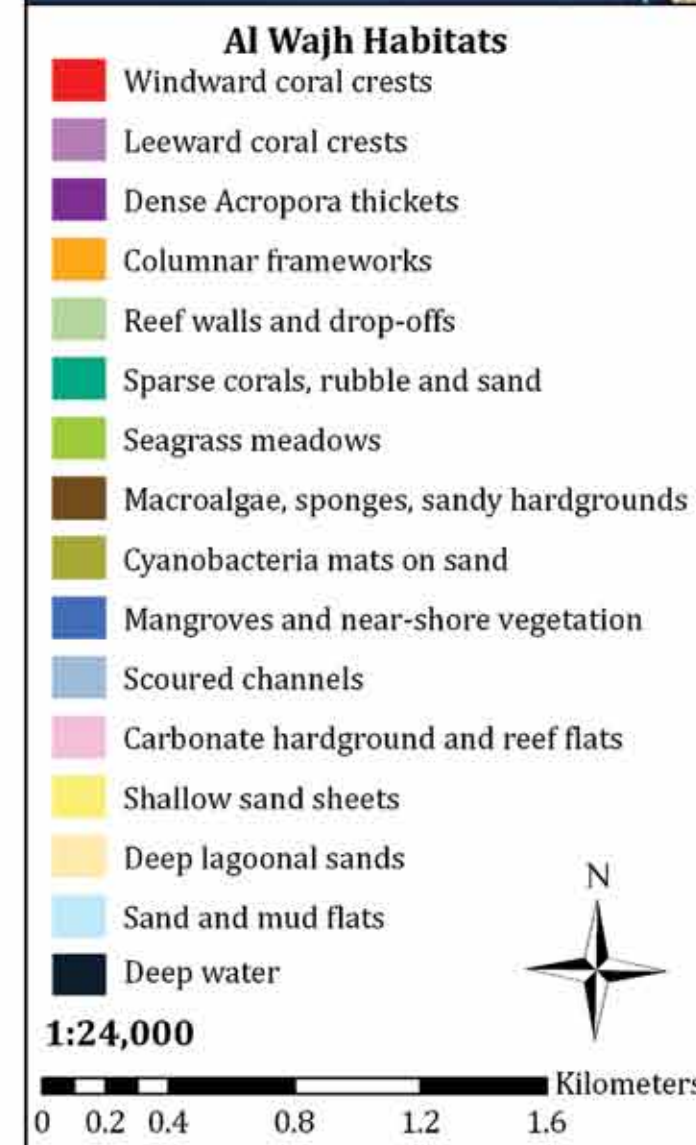
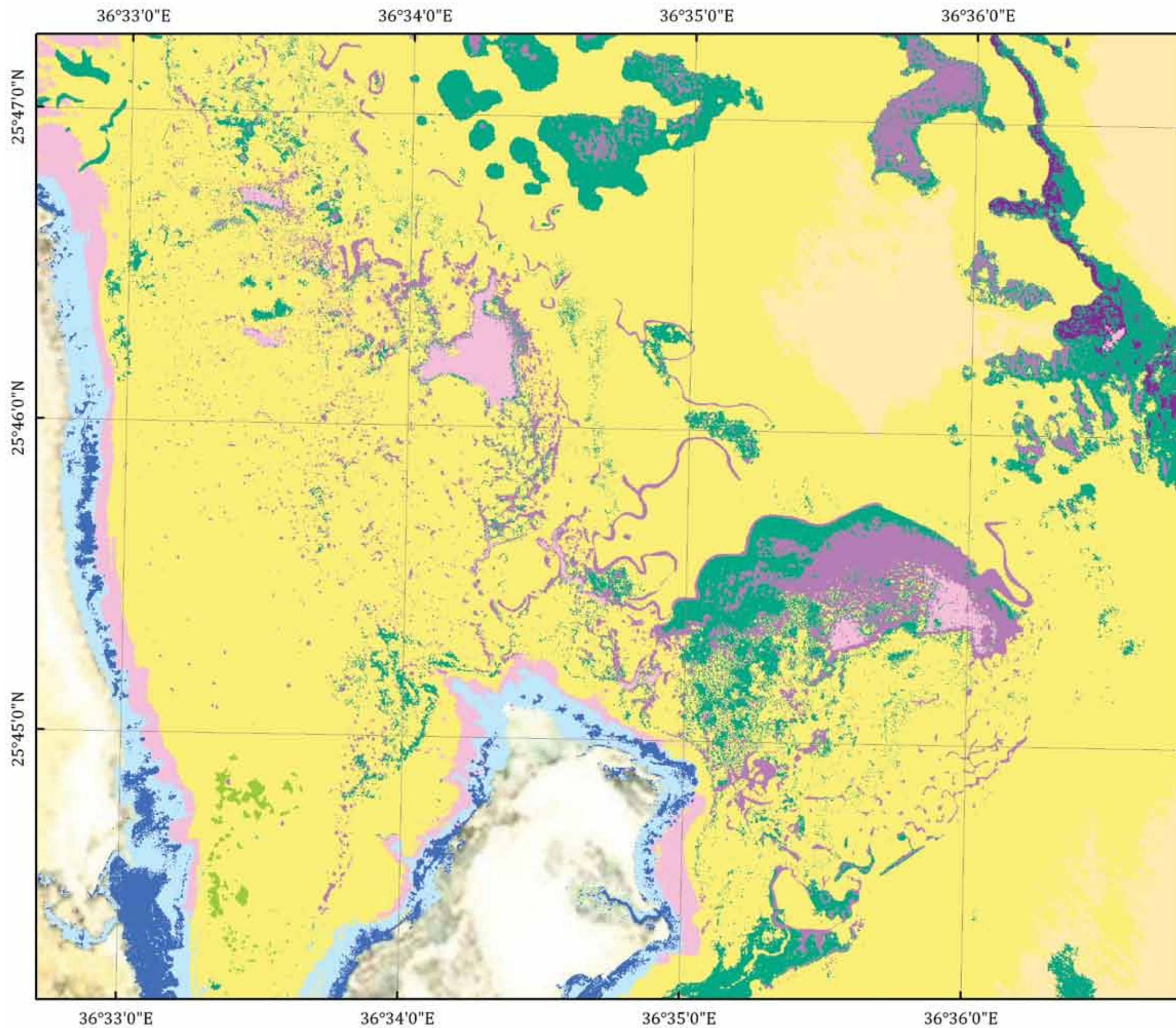


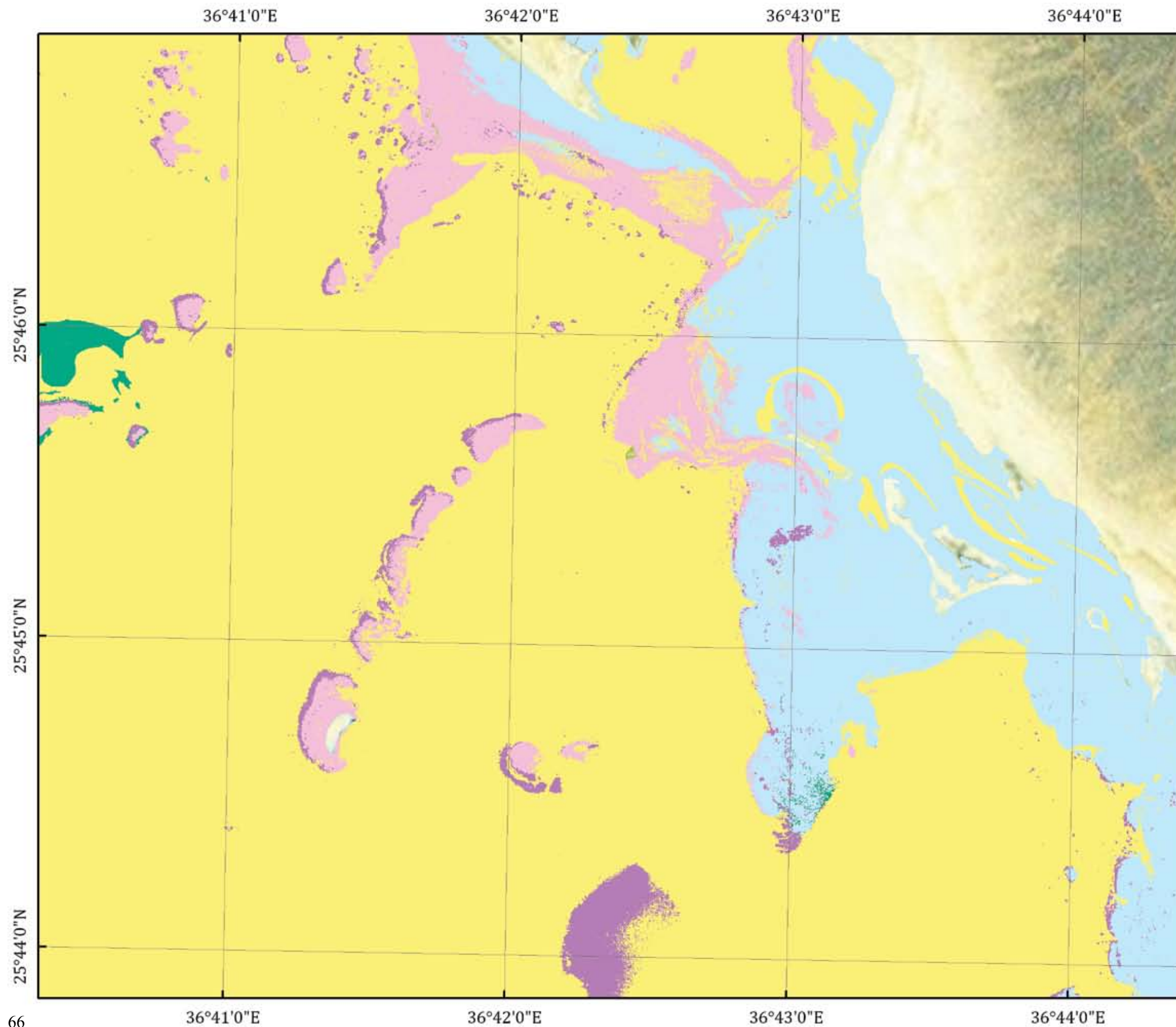
**Al Wajh Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
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- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:24,000**

N  
  
 Kilometers  
 0 0.2 0.4 0.8 1.2 1.6






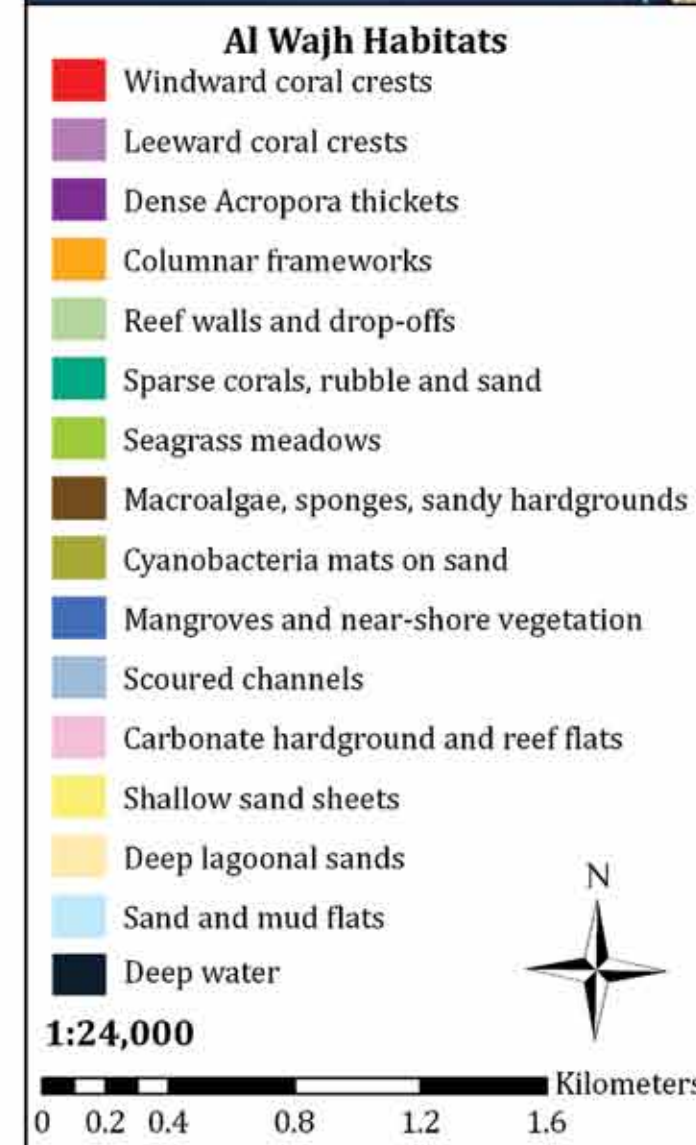
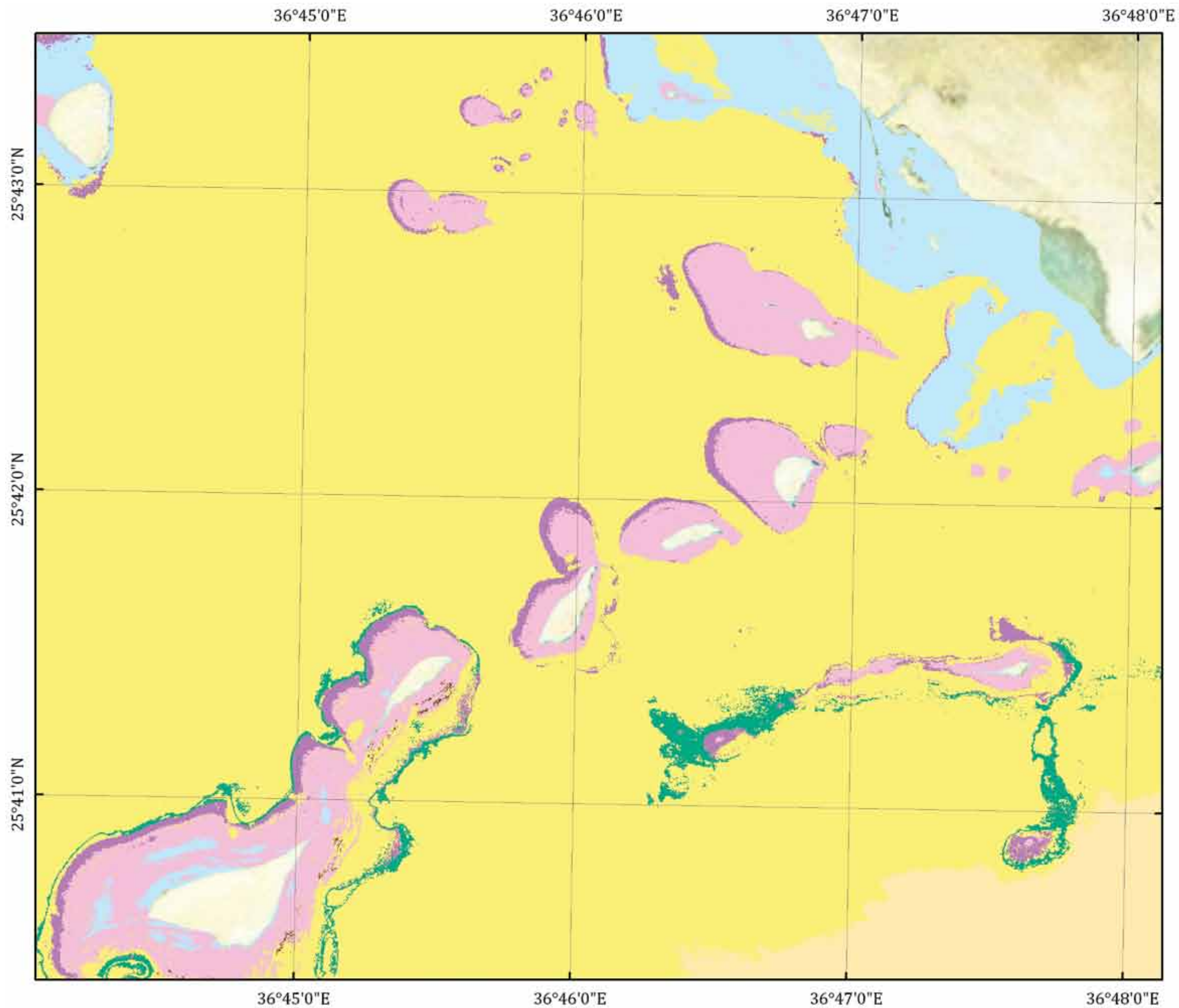
**Al Wajh Habitats**

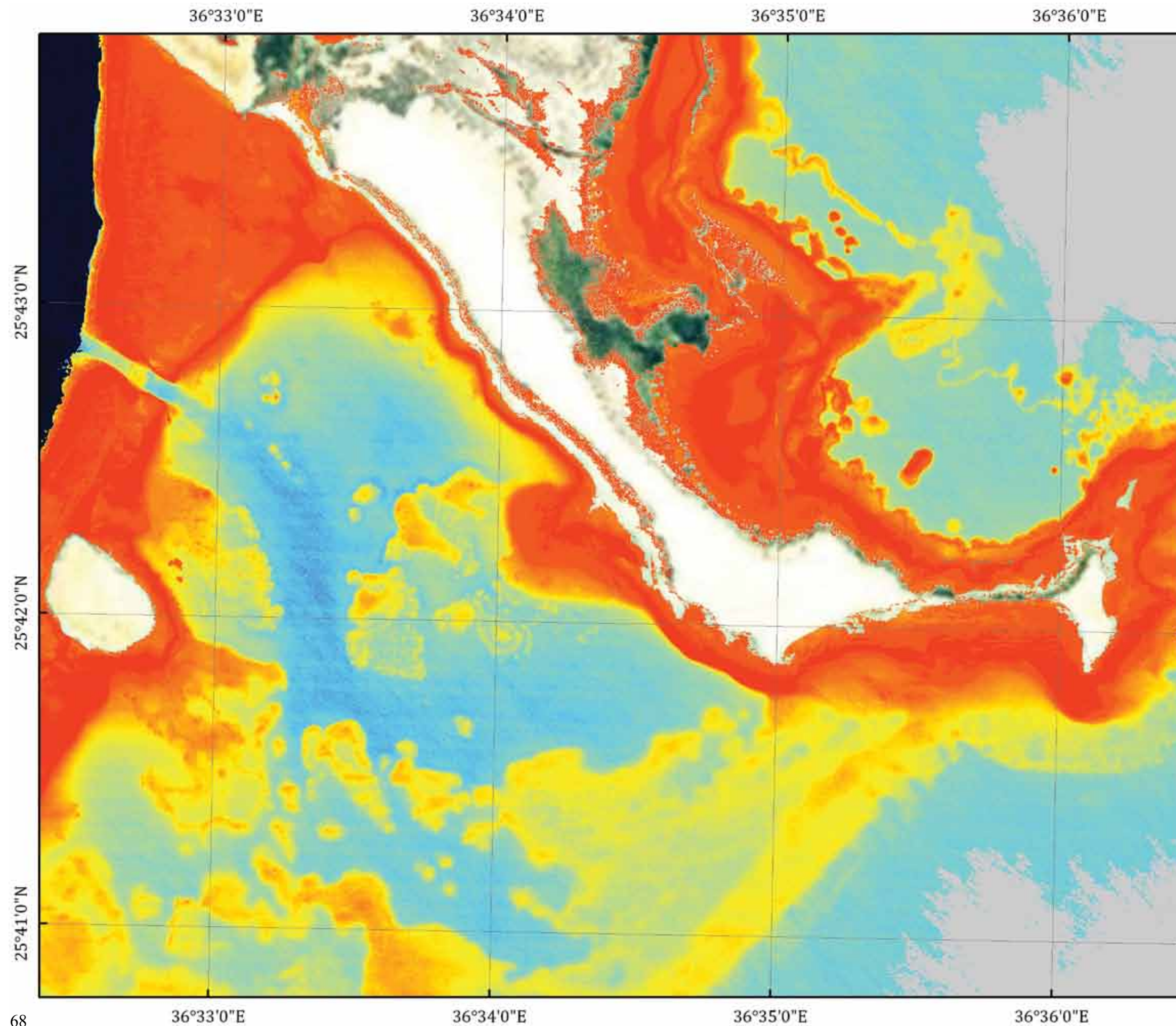
- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
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- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:24,000**

0 0.2 0.4 0.8 1.2 1.6 Kilometers

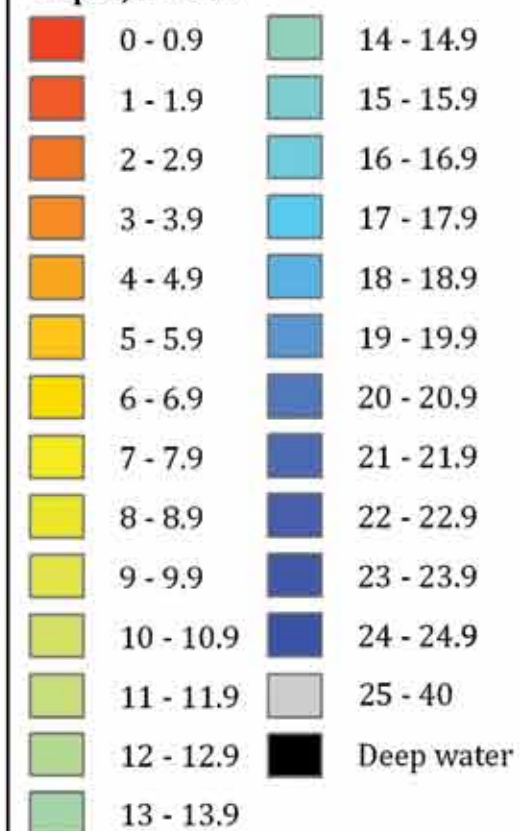






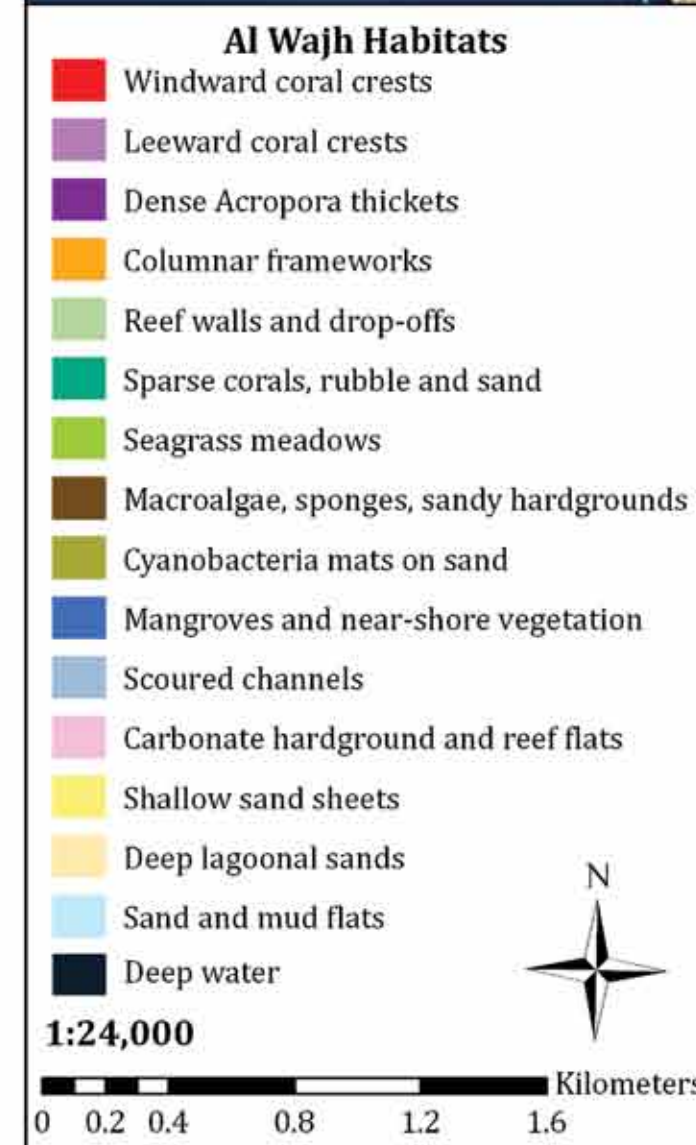
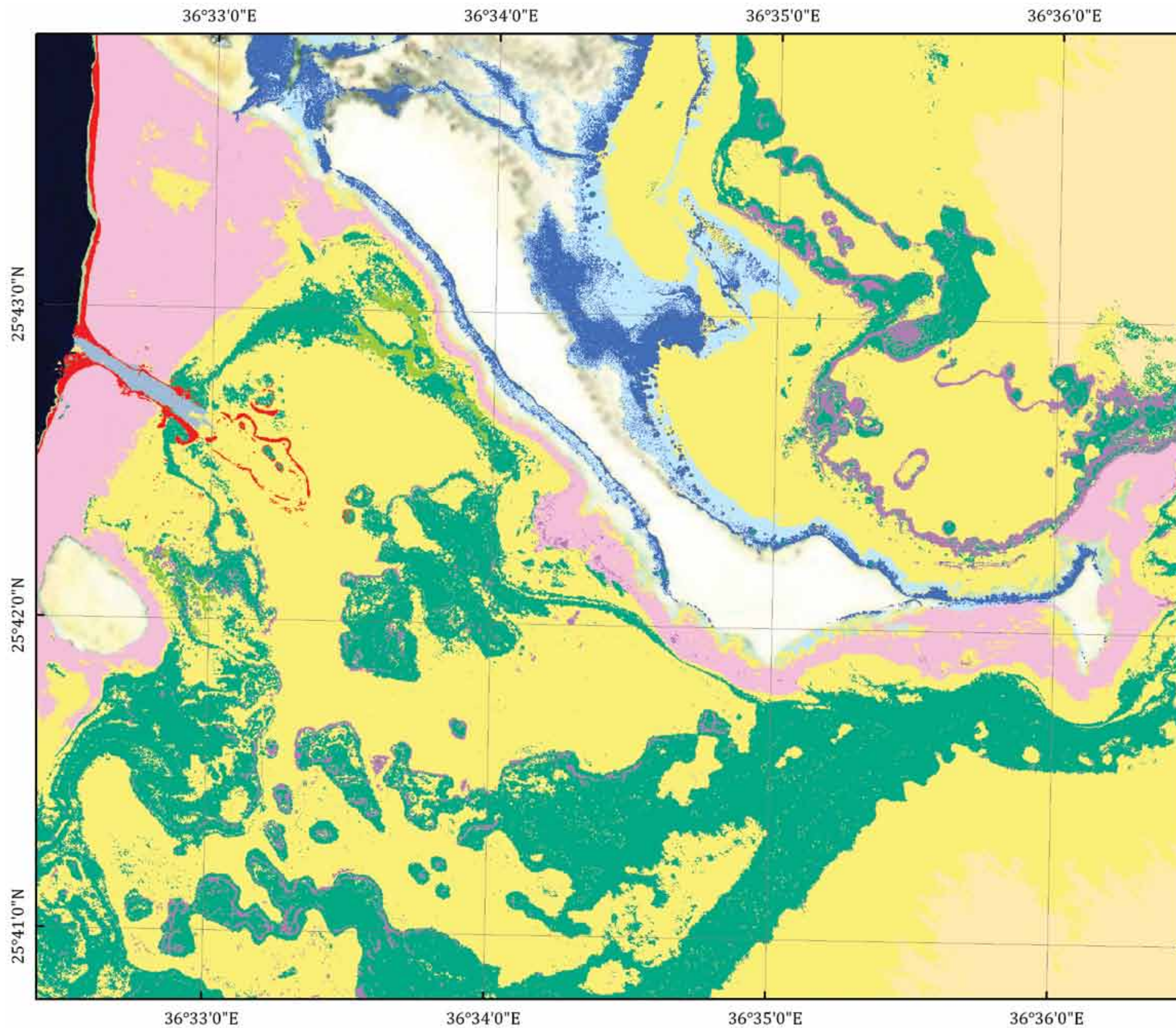
### Al Wajh Bathymetry

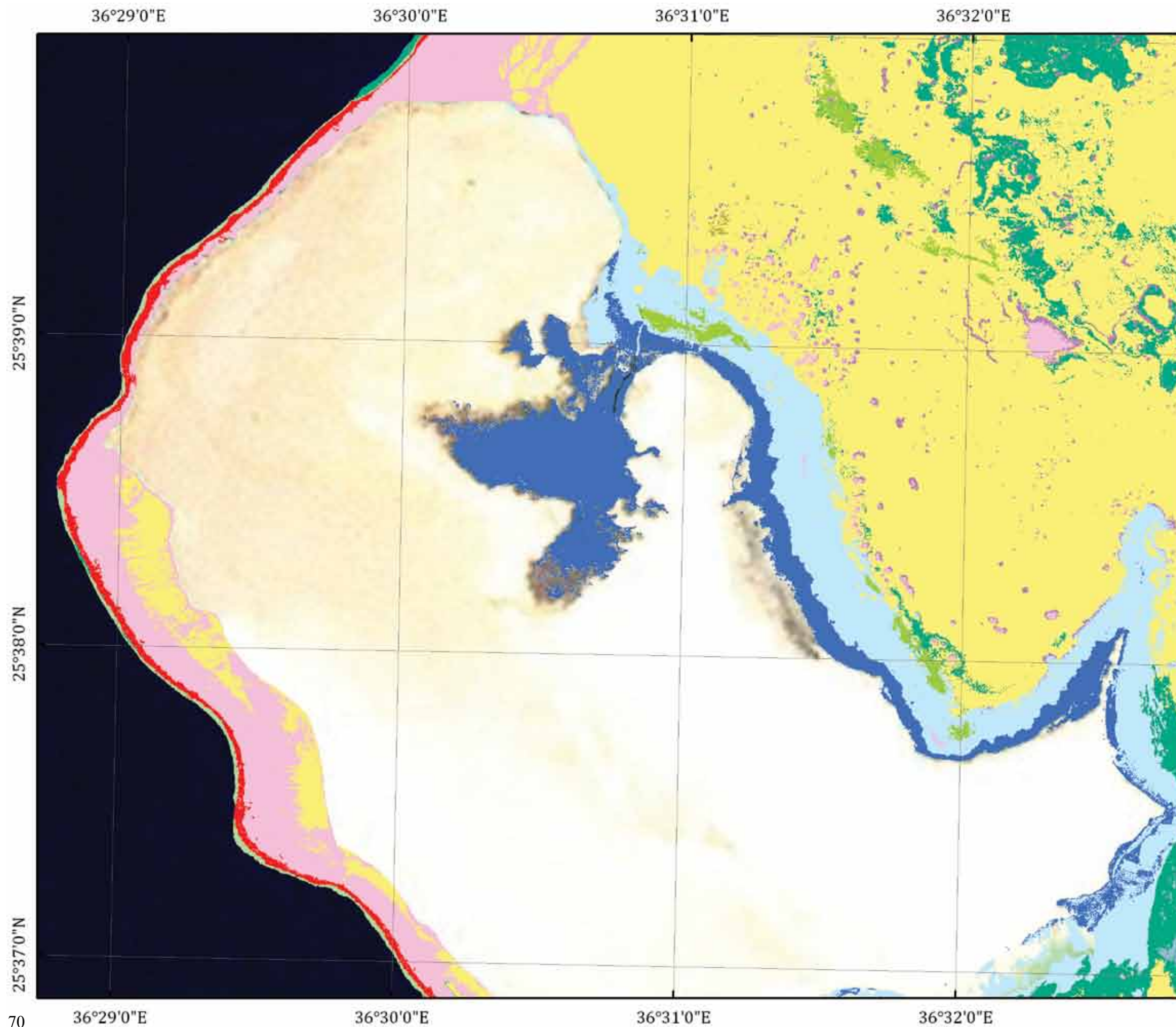
Depth, meters



1:24,000

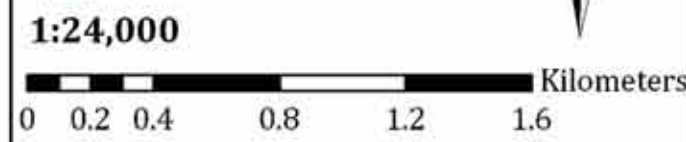


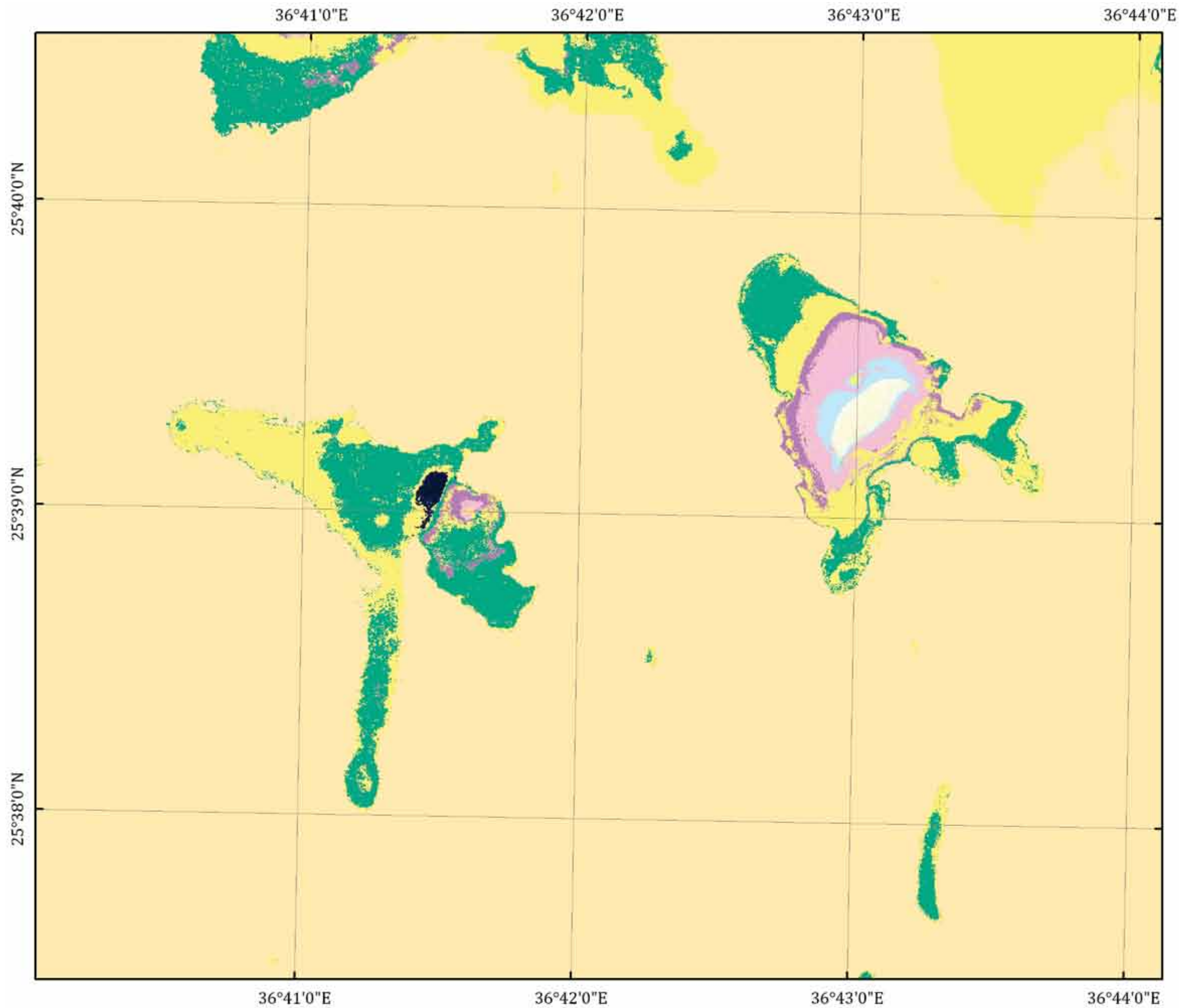




**Al Wajh Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
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- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water





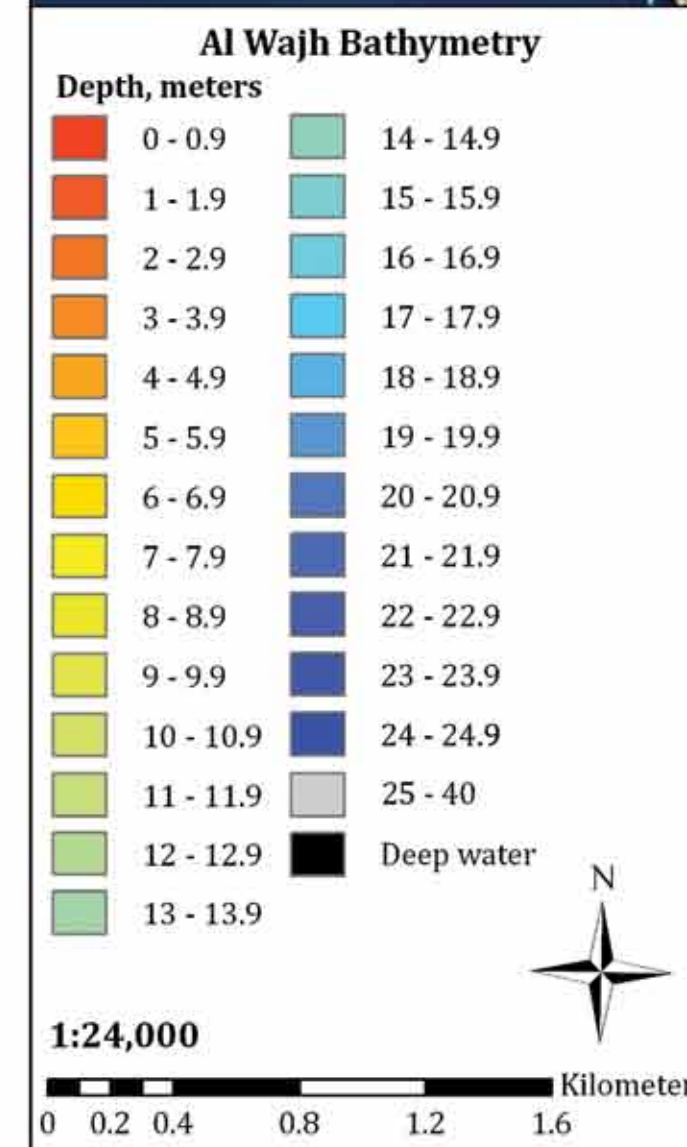
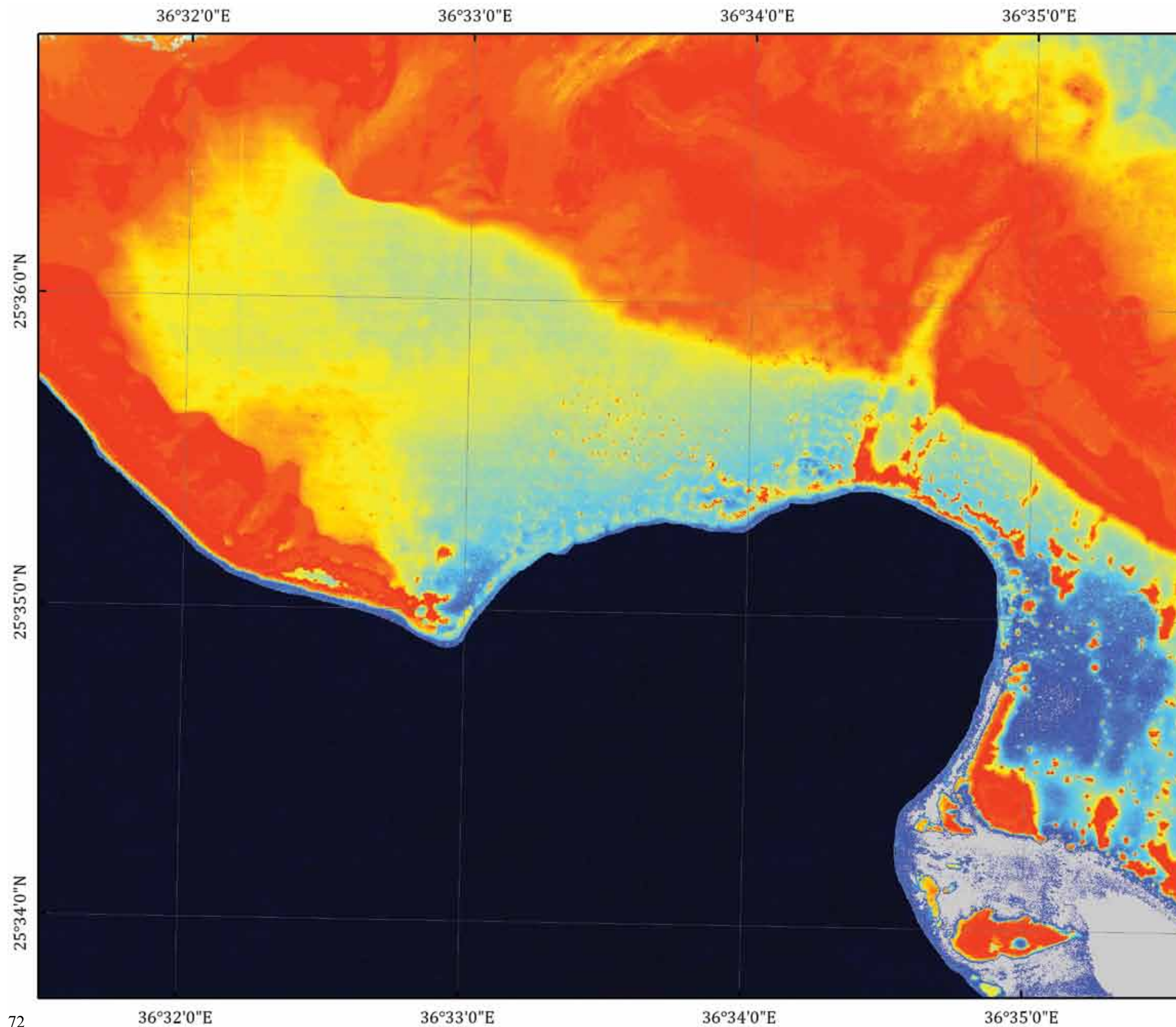
**Al Wajh Habitats**

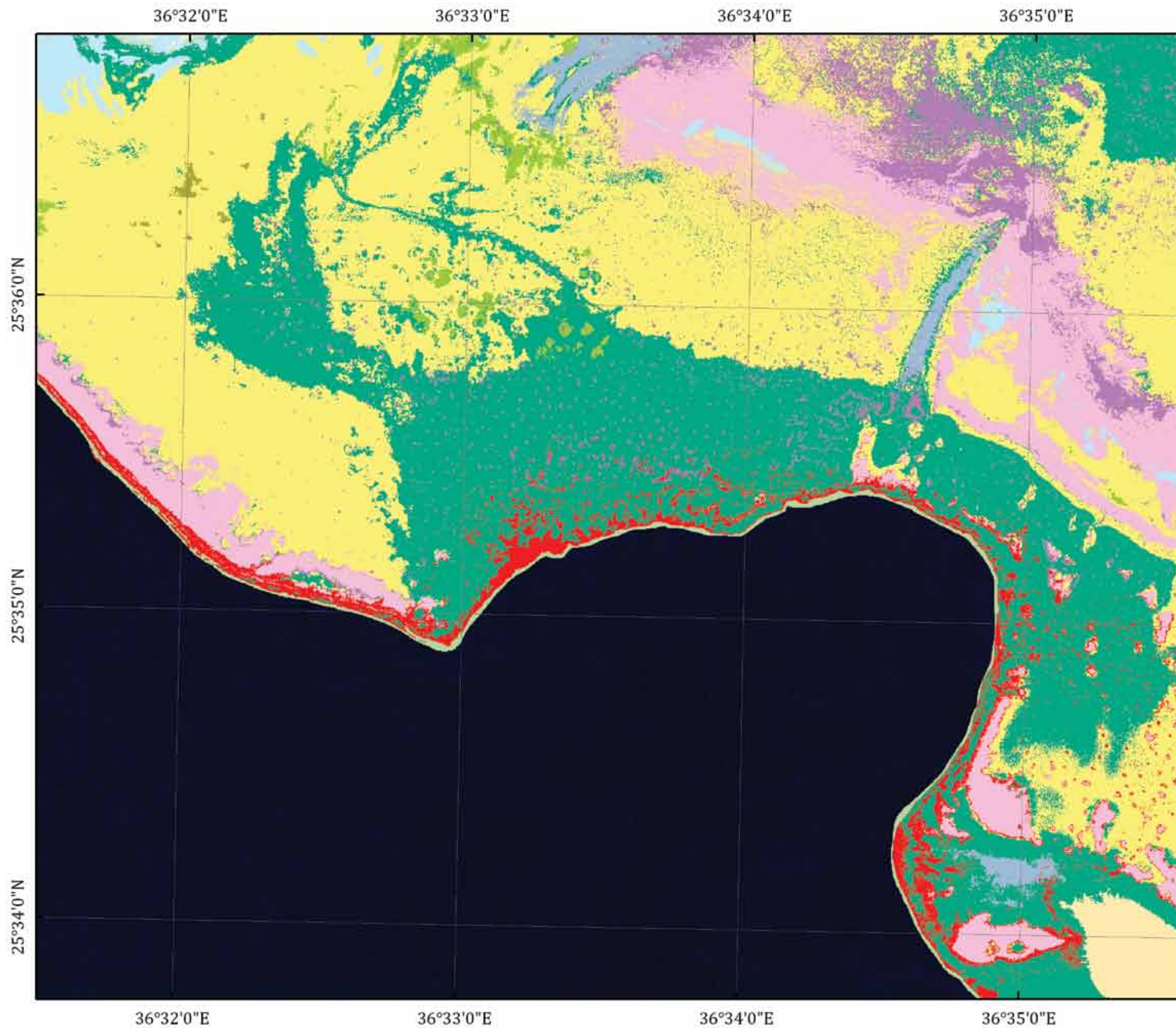
- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
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- Mangroves and near-shore vegetation
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:24,000**

Kilometers





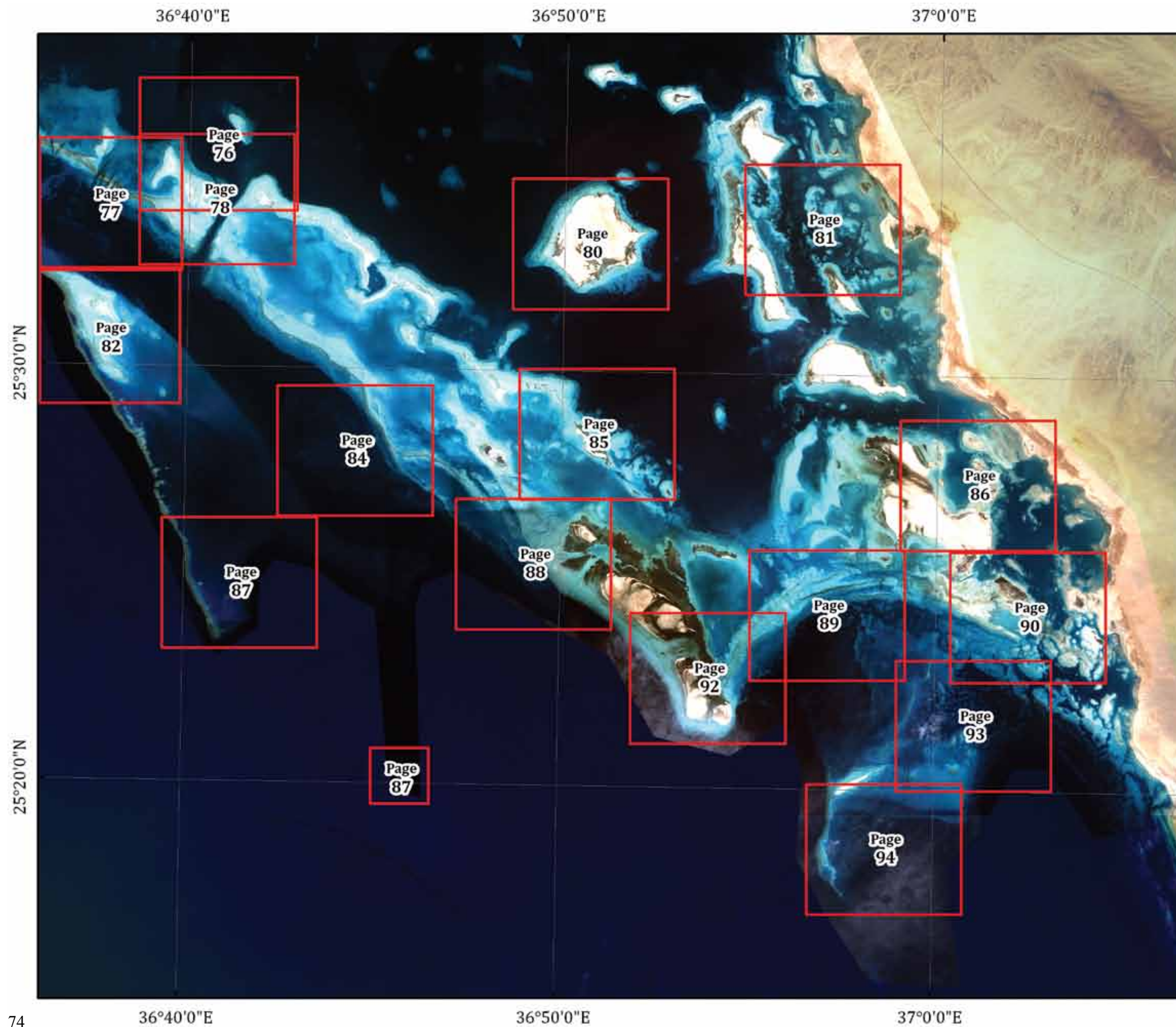


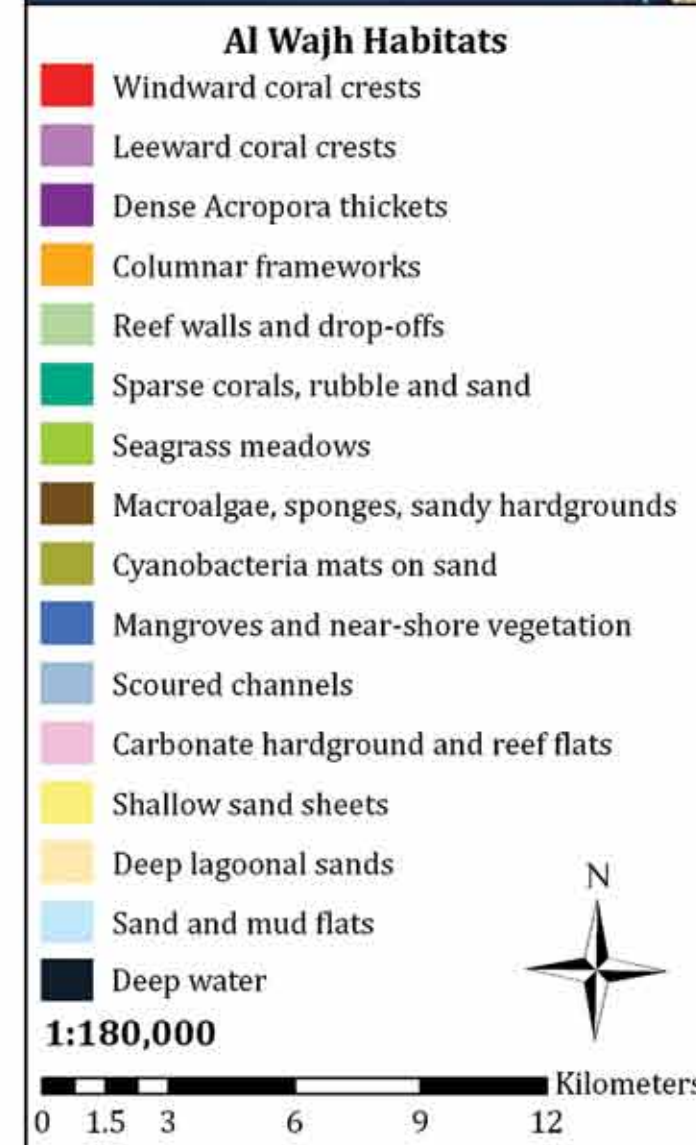
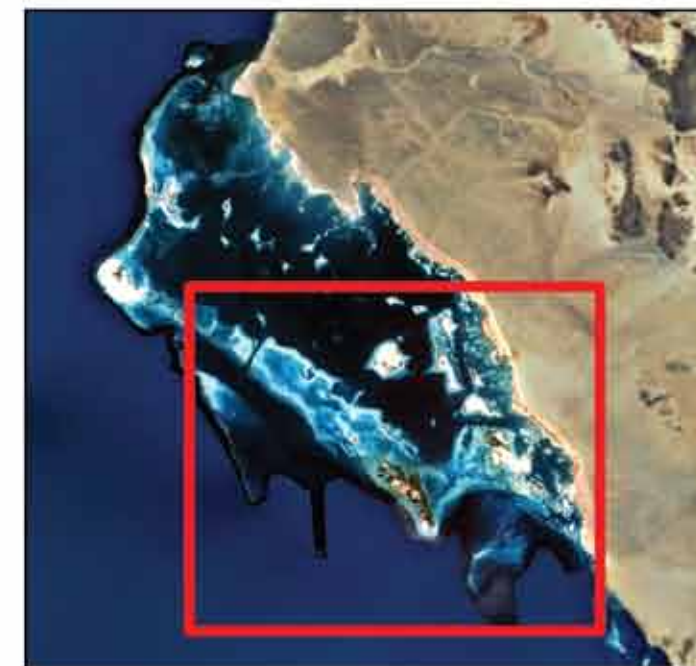
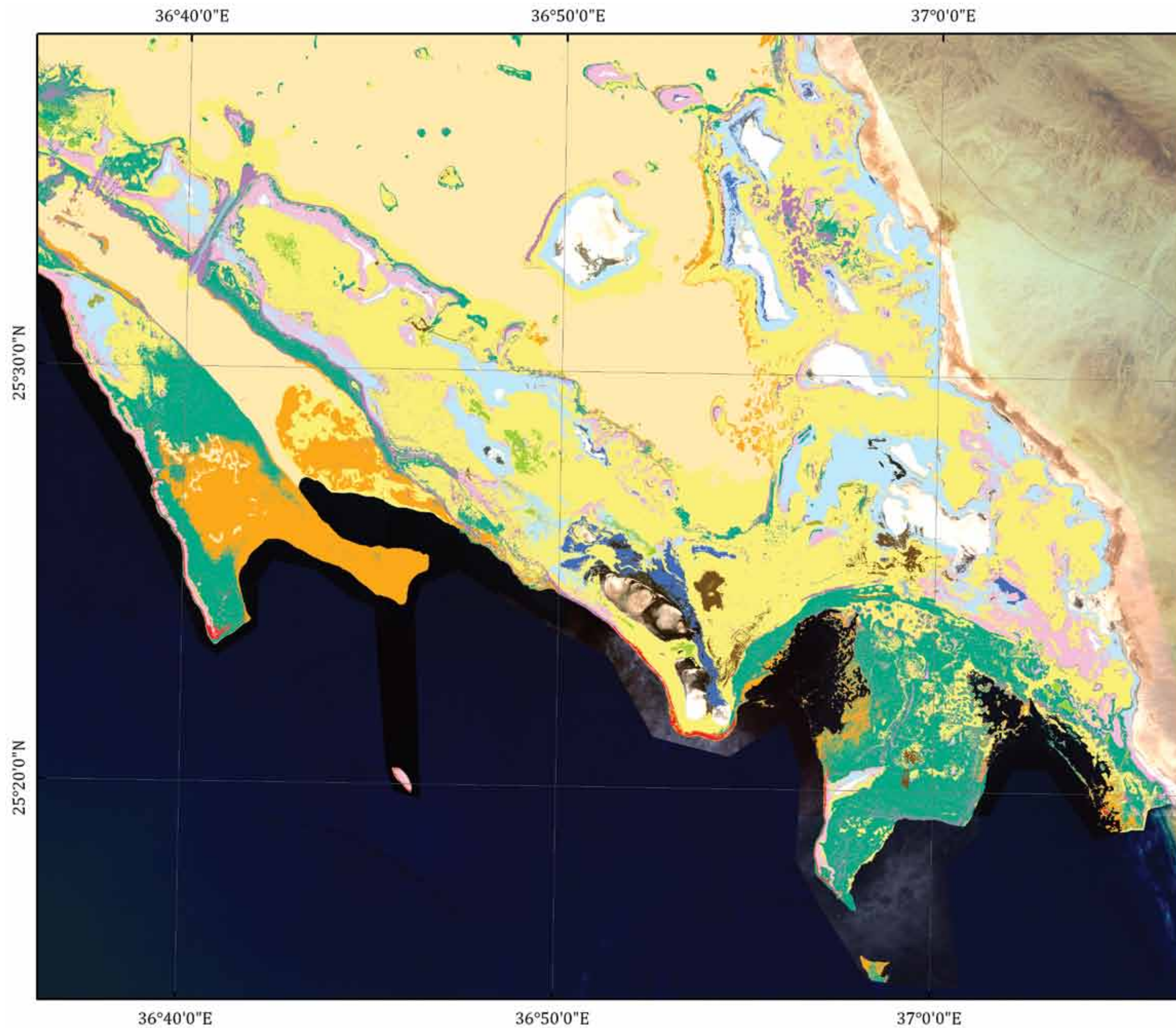
**Al Wajh Habitats**

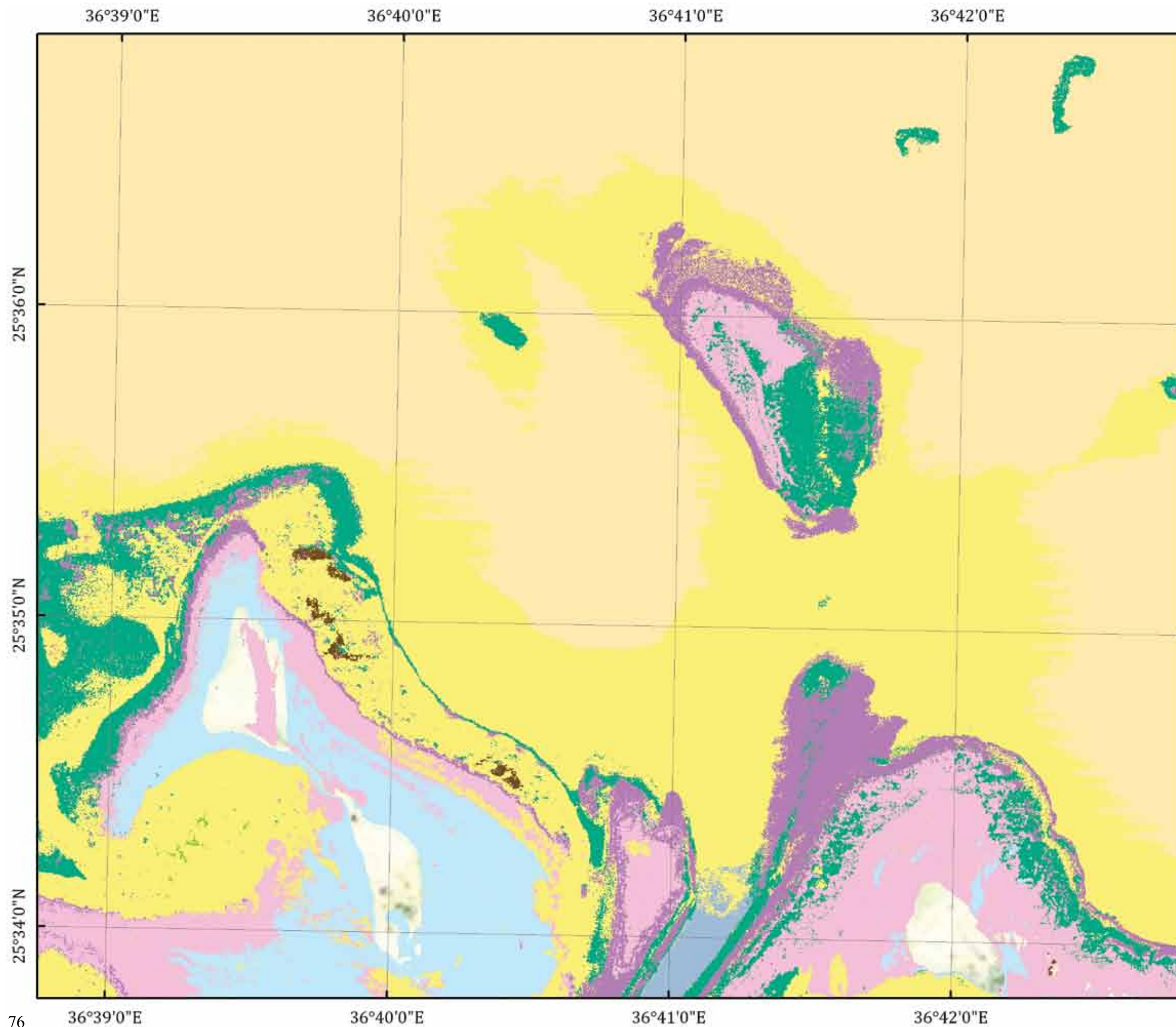
- Windward coral crests
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- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:24,000**

Kilometers





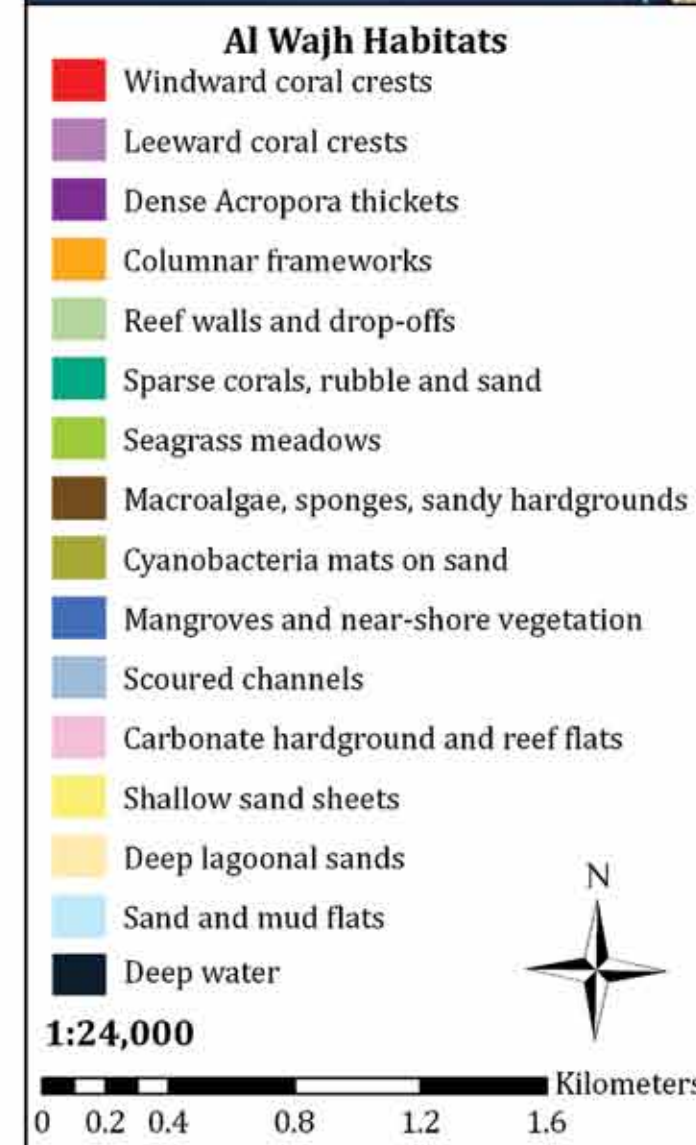
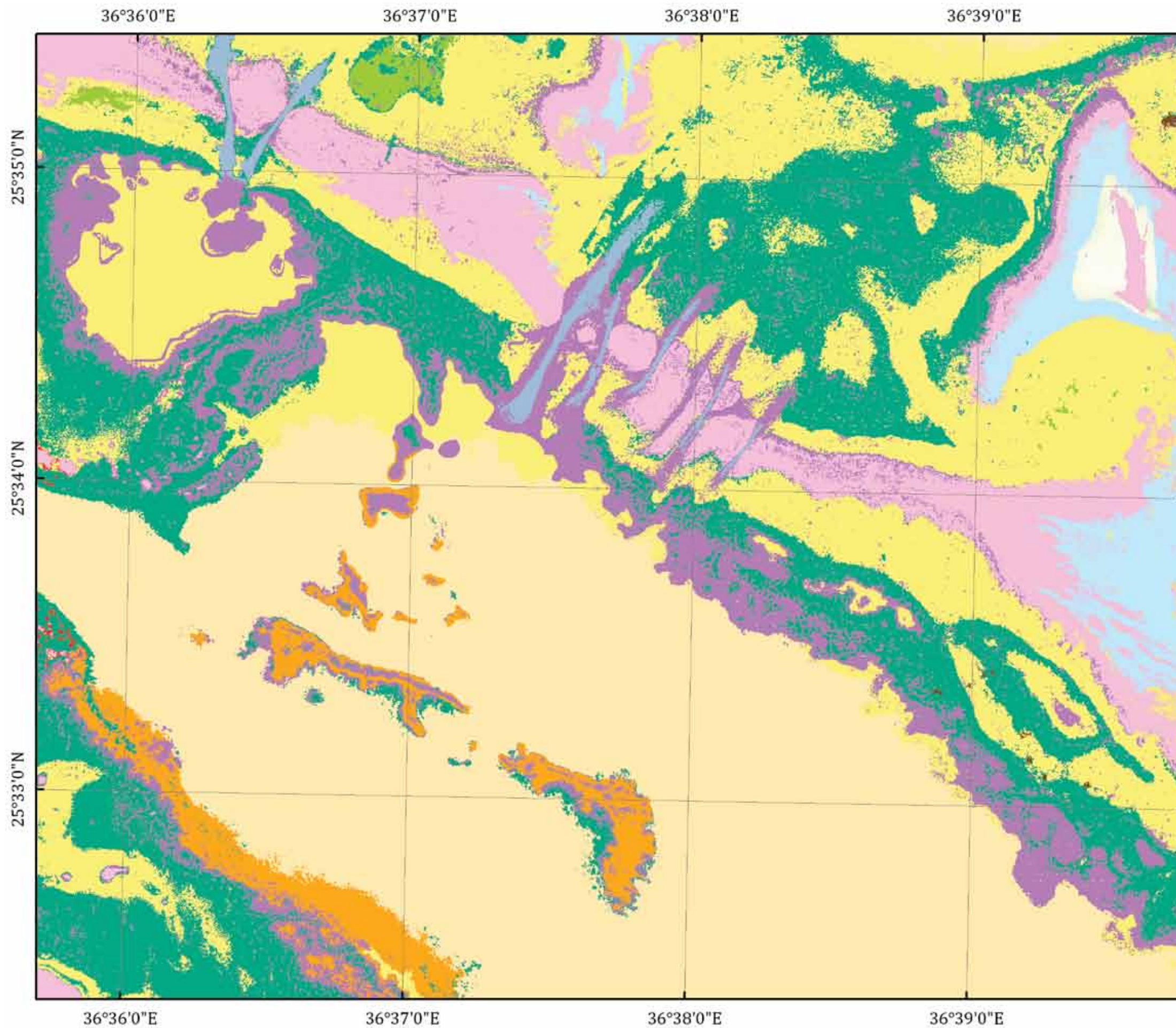


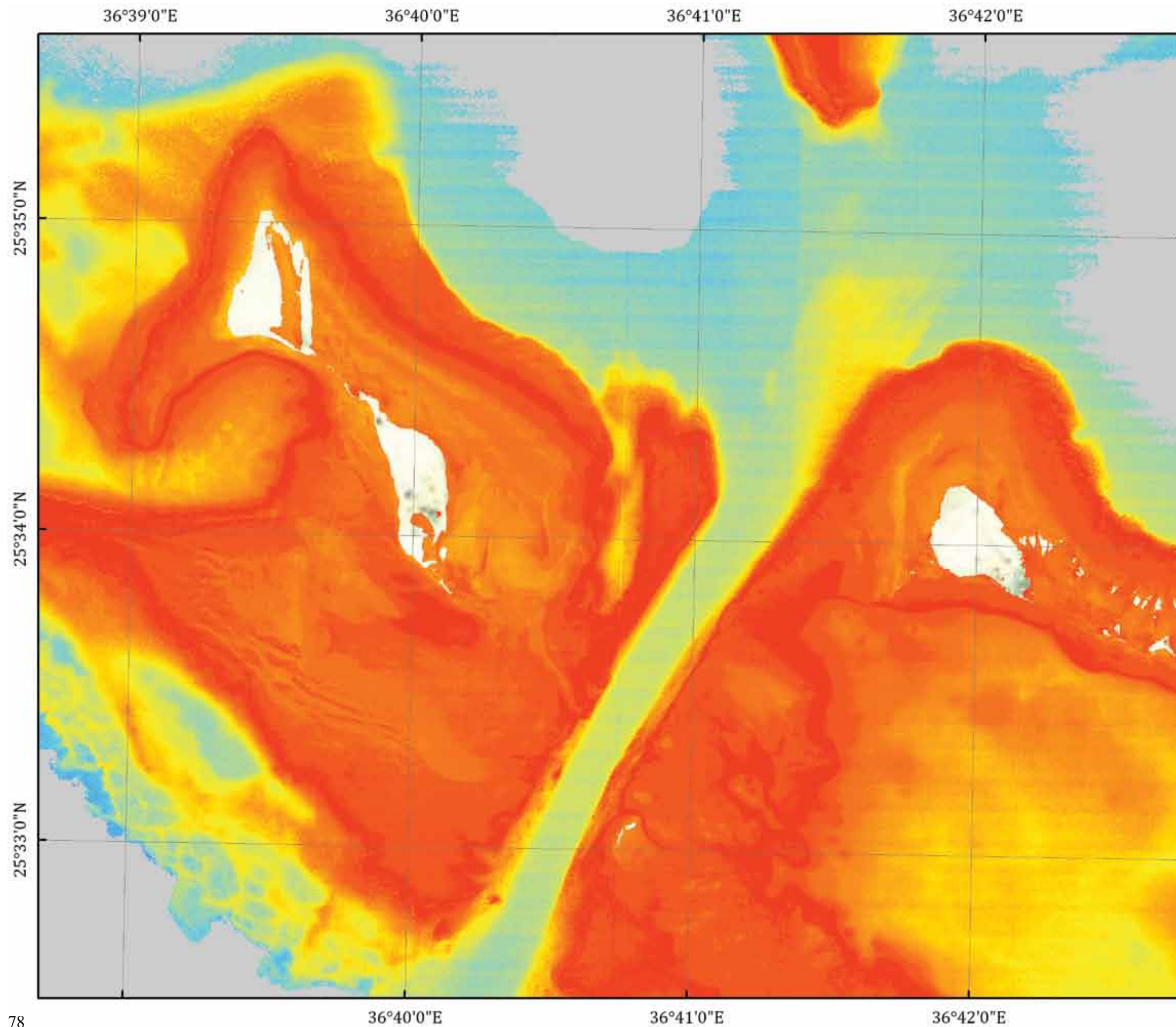
**Al Wajh Habitats**

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- Leeward coral crests
- Dense Acropora thickets
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- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:24,000**







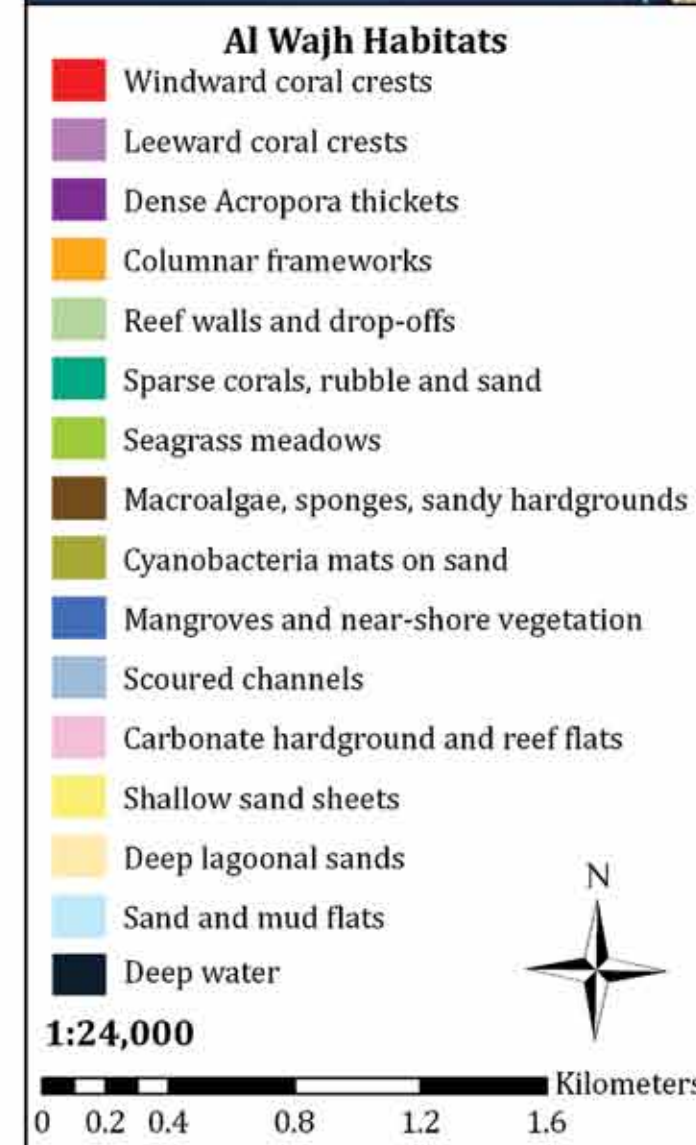
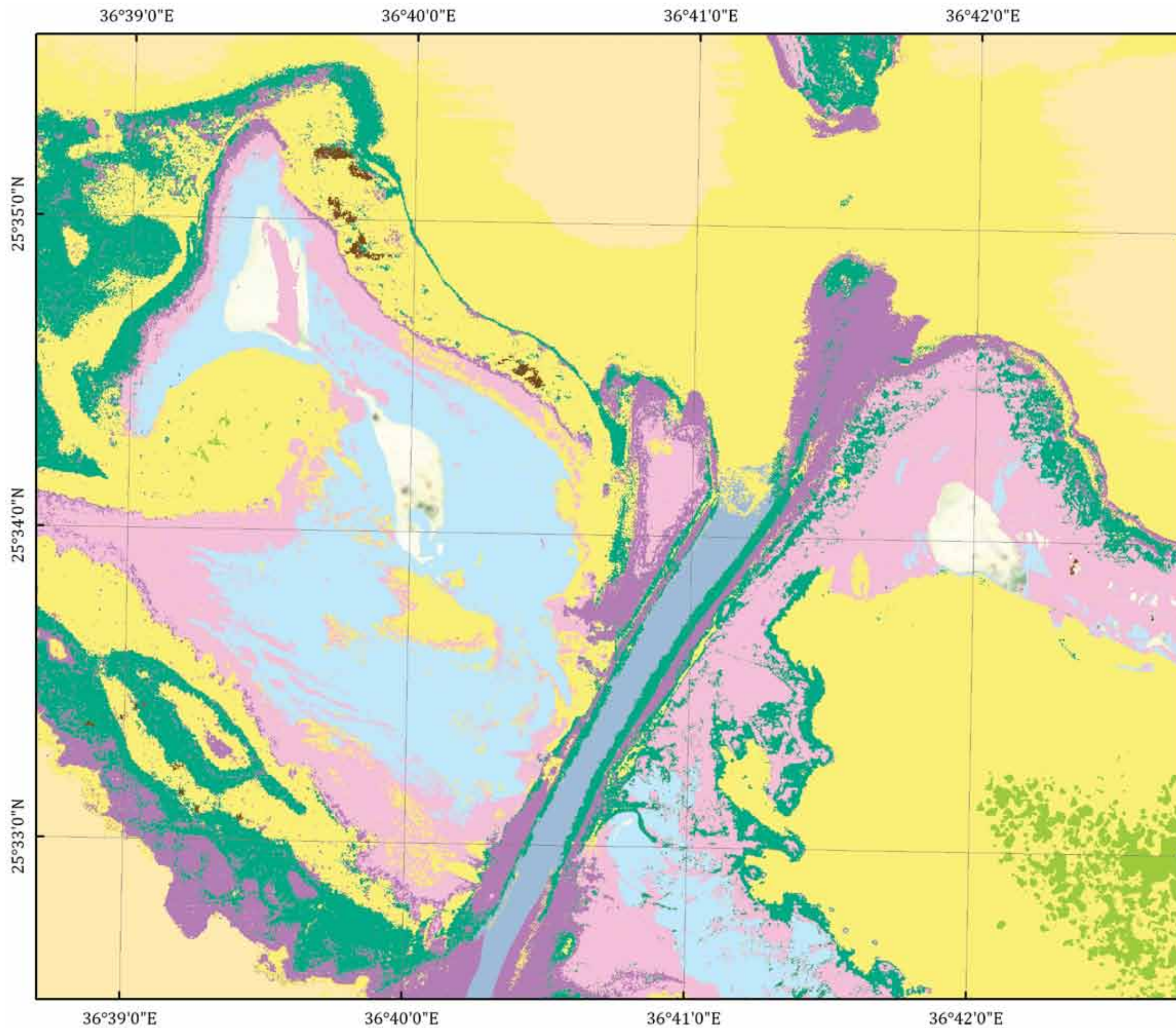
**Al Wajh Bathymetry**

**Depth, meters**

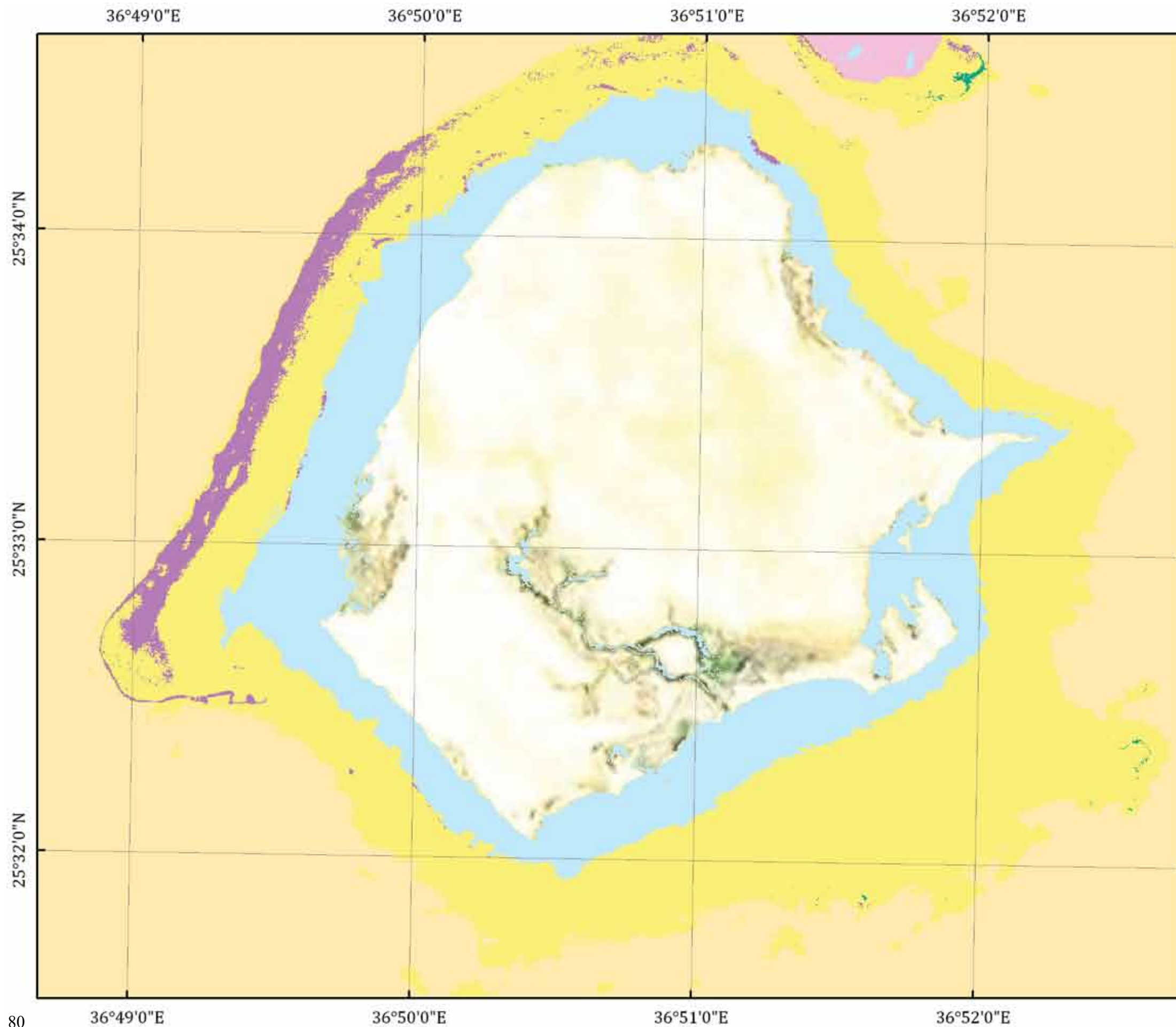
0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

**1:24,000**



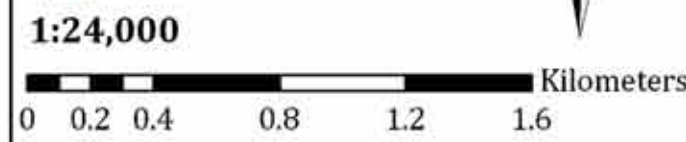


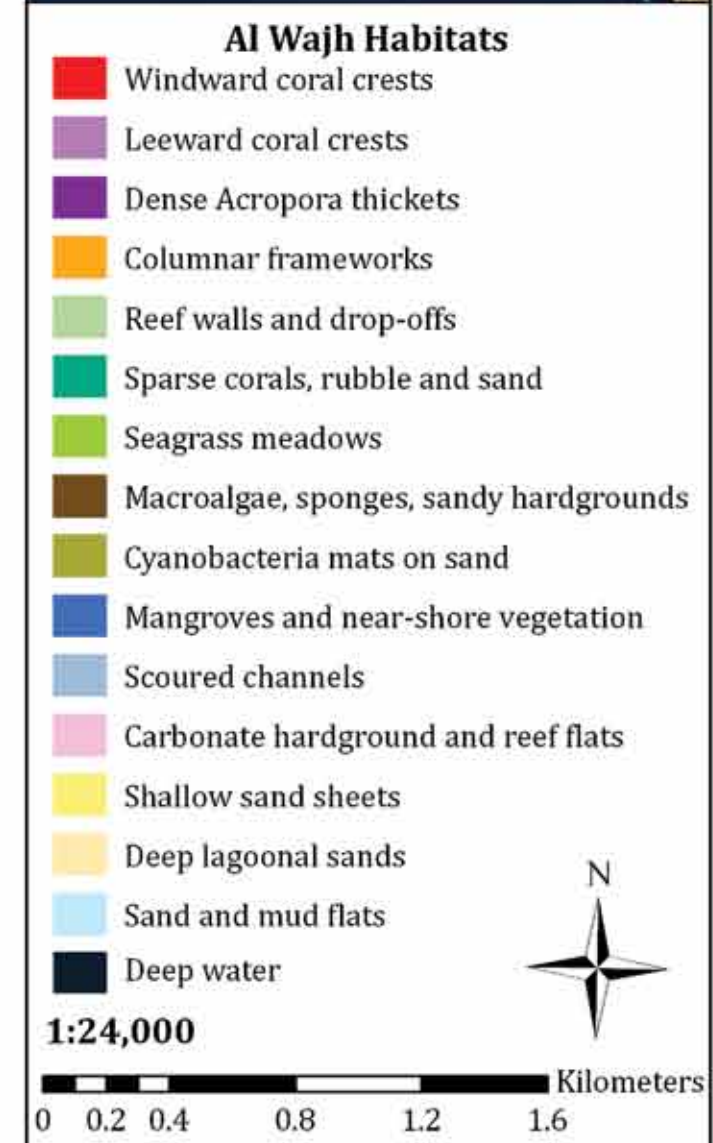
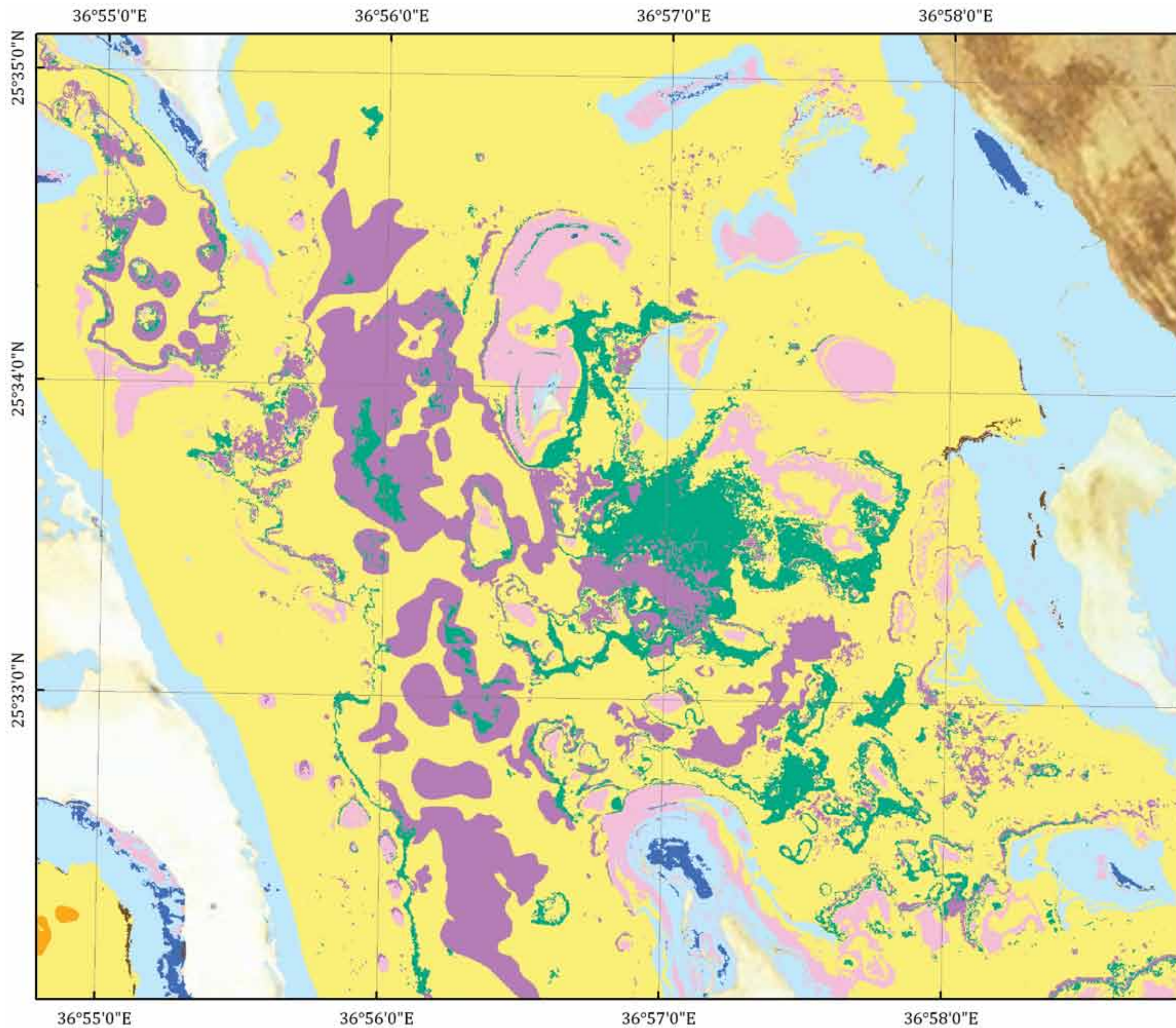


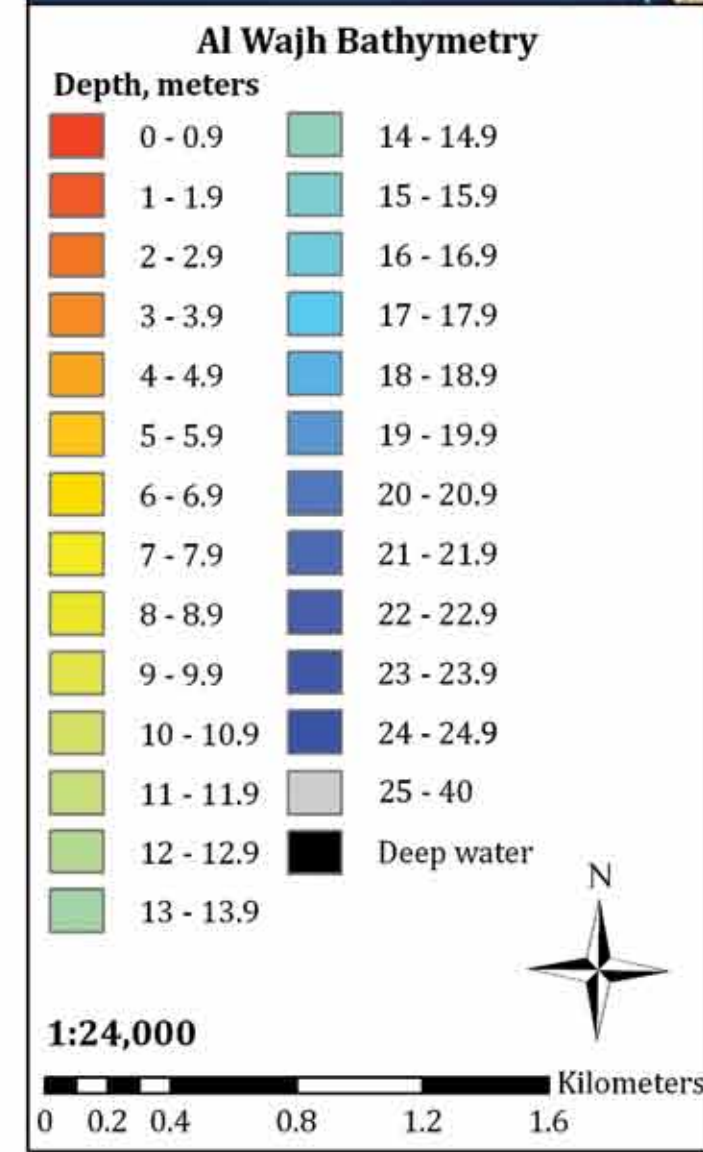
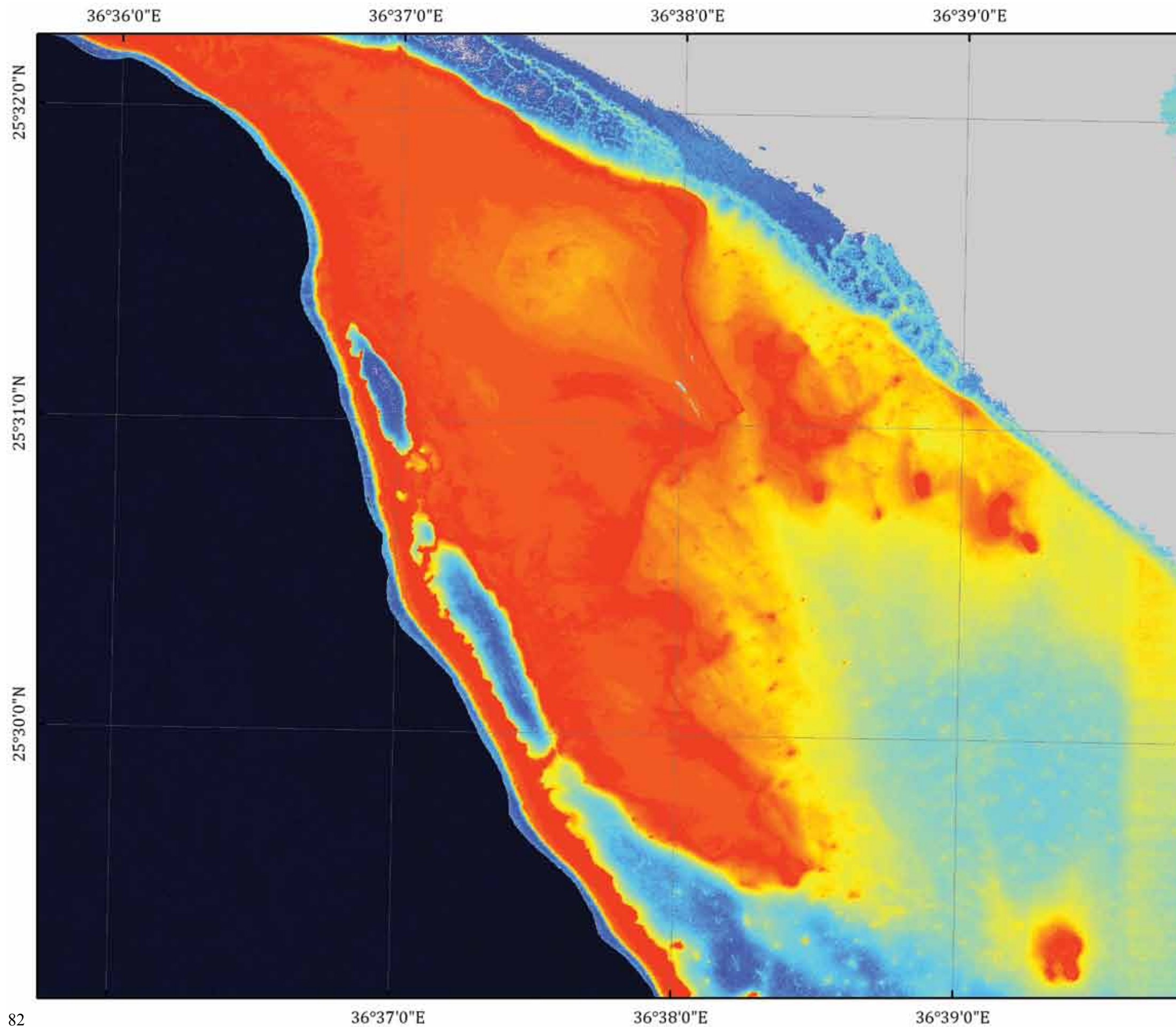


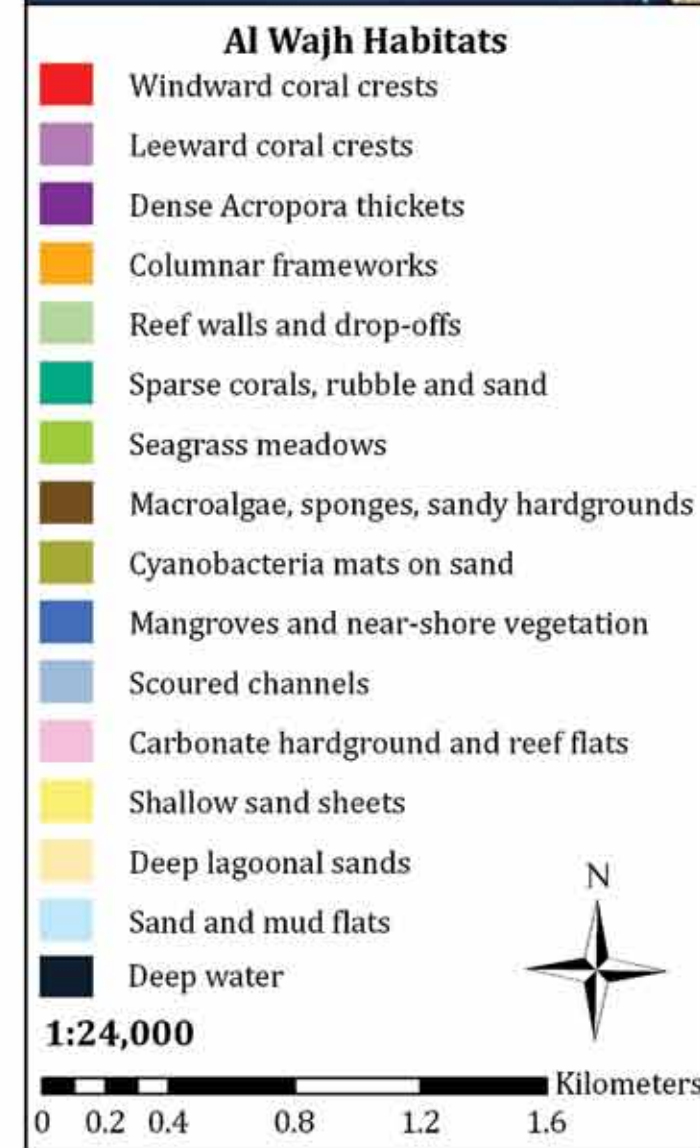
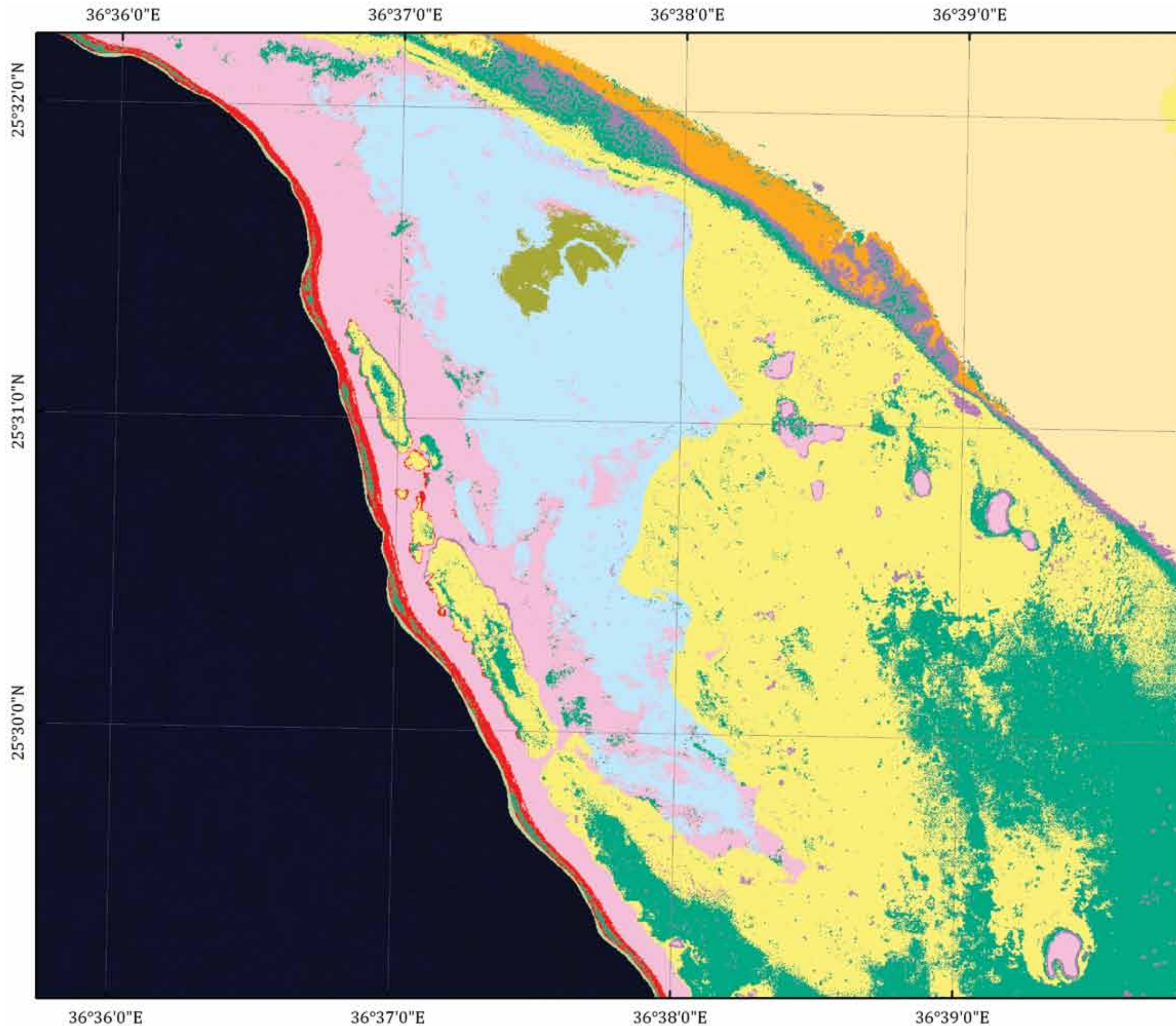
**Al Wajh Habitats**

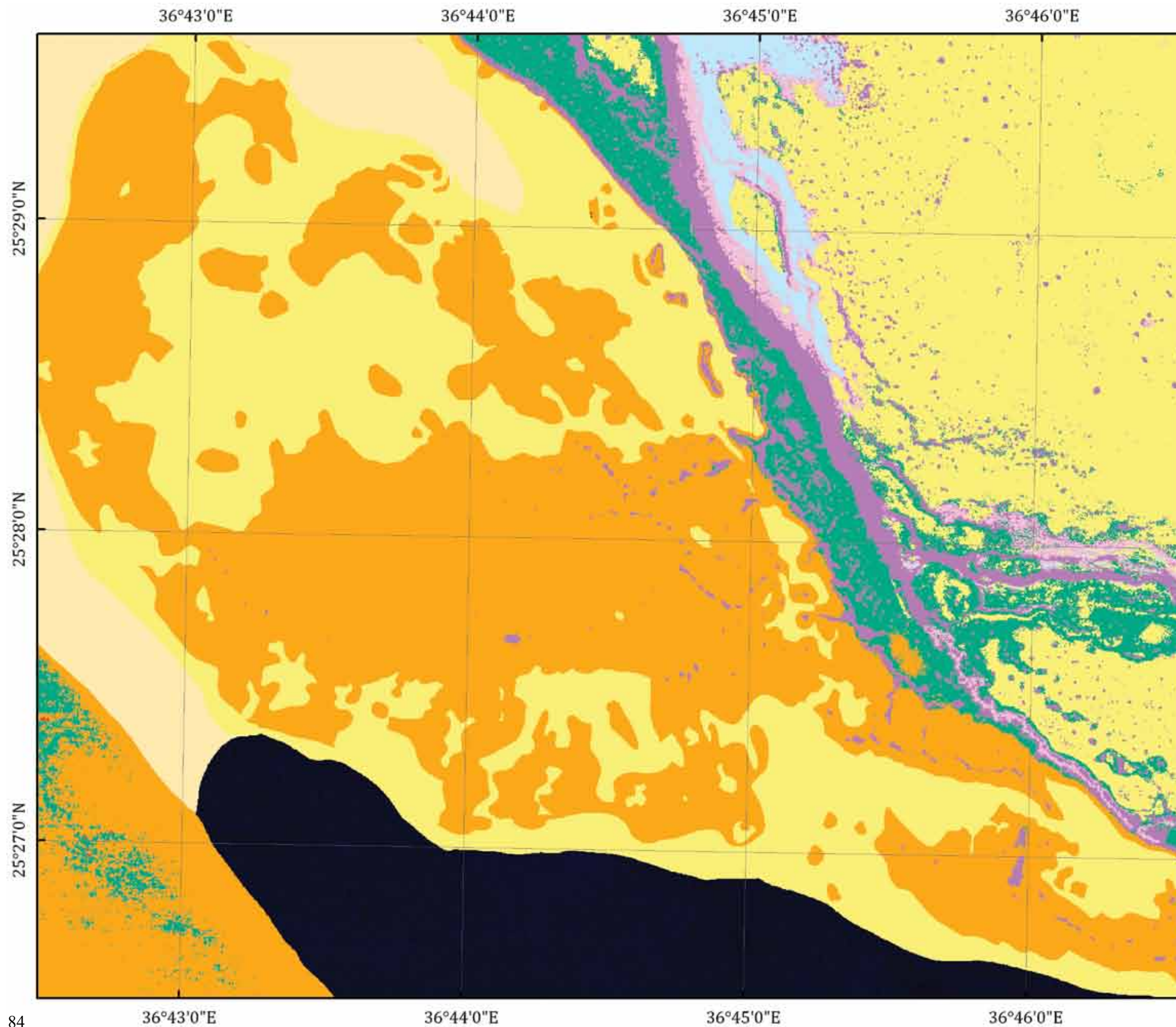
- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
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- Mangroves and near-shore vegetation
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water









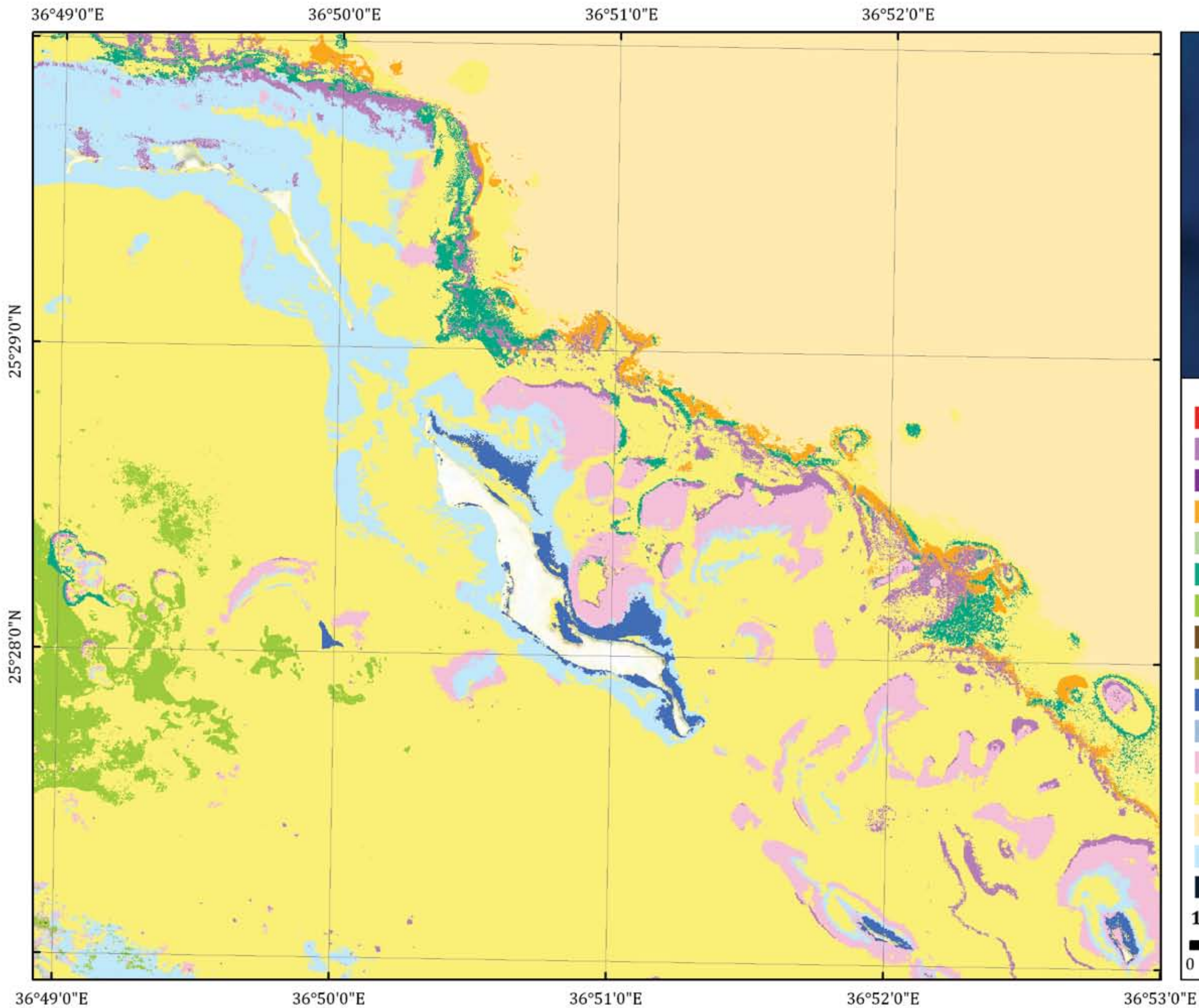


**Al Wajh Habitats**

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- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:24,000**



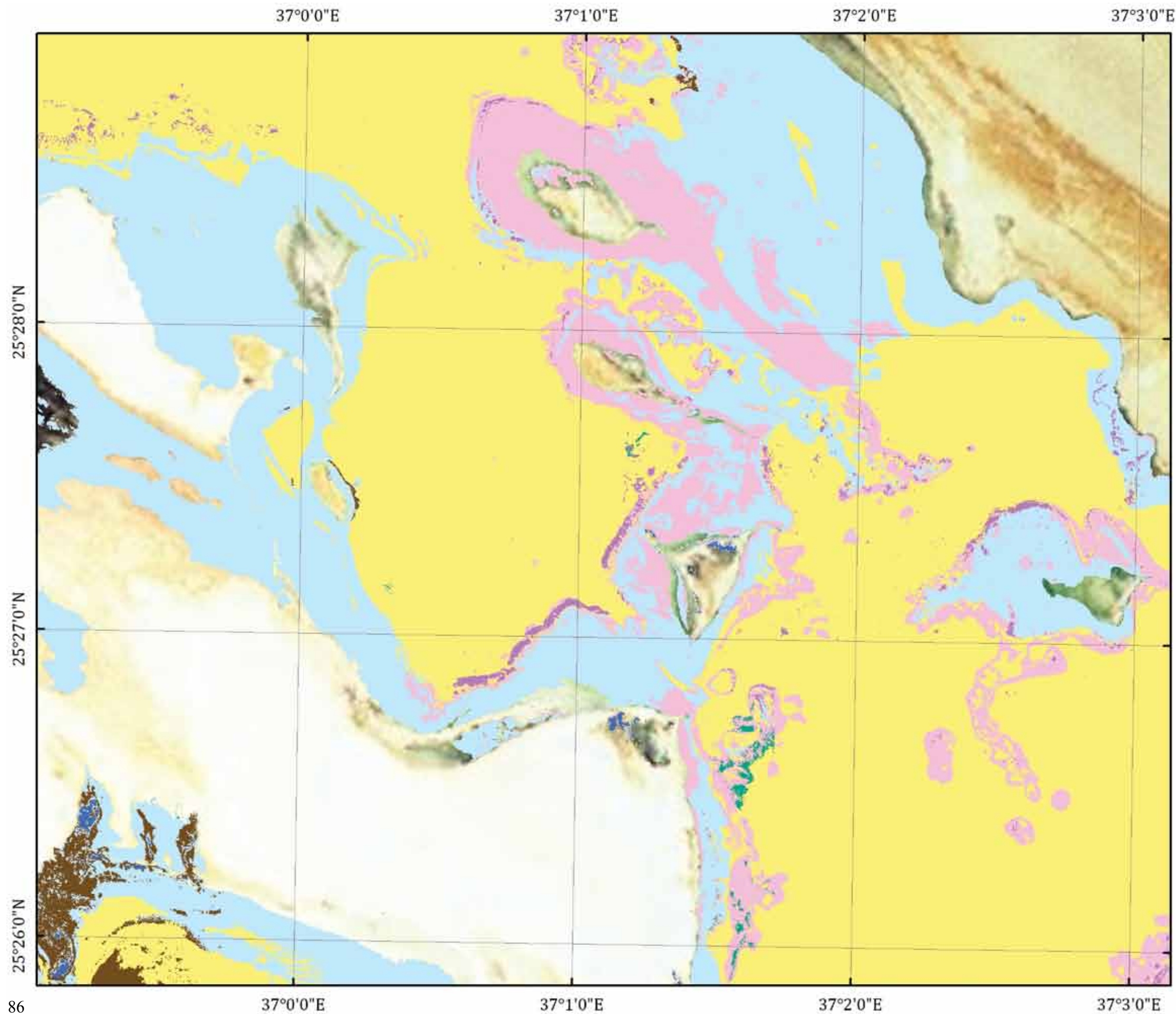


**Al Wajh Habitats**

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- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

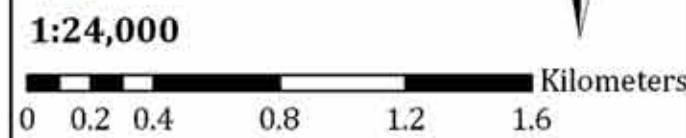
**1:24,000**

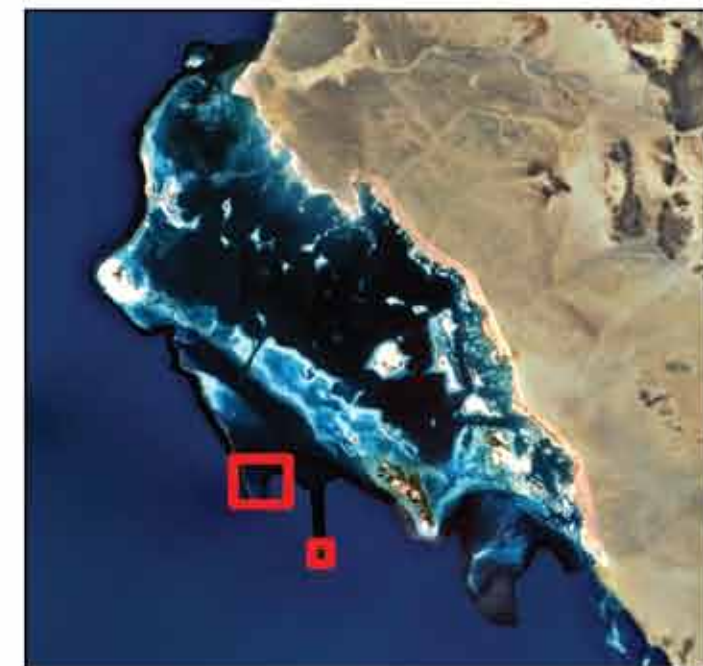
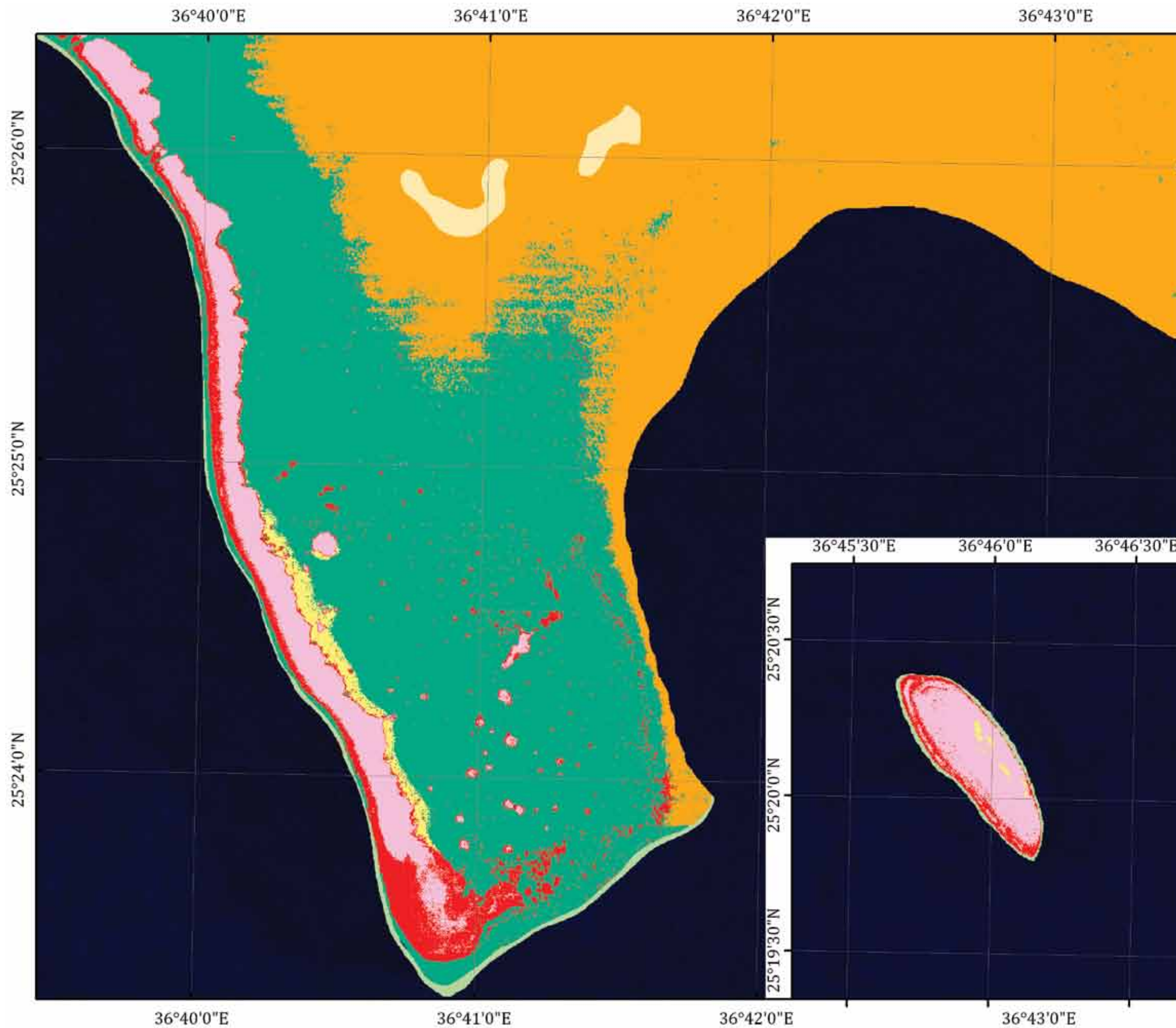
Kilometers



**Al Wajh Habitats**

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- Shallow sand sheets
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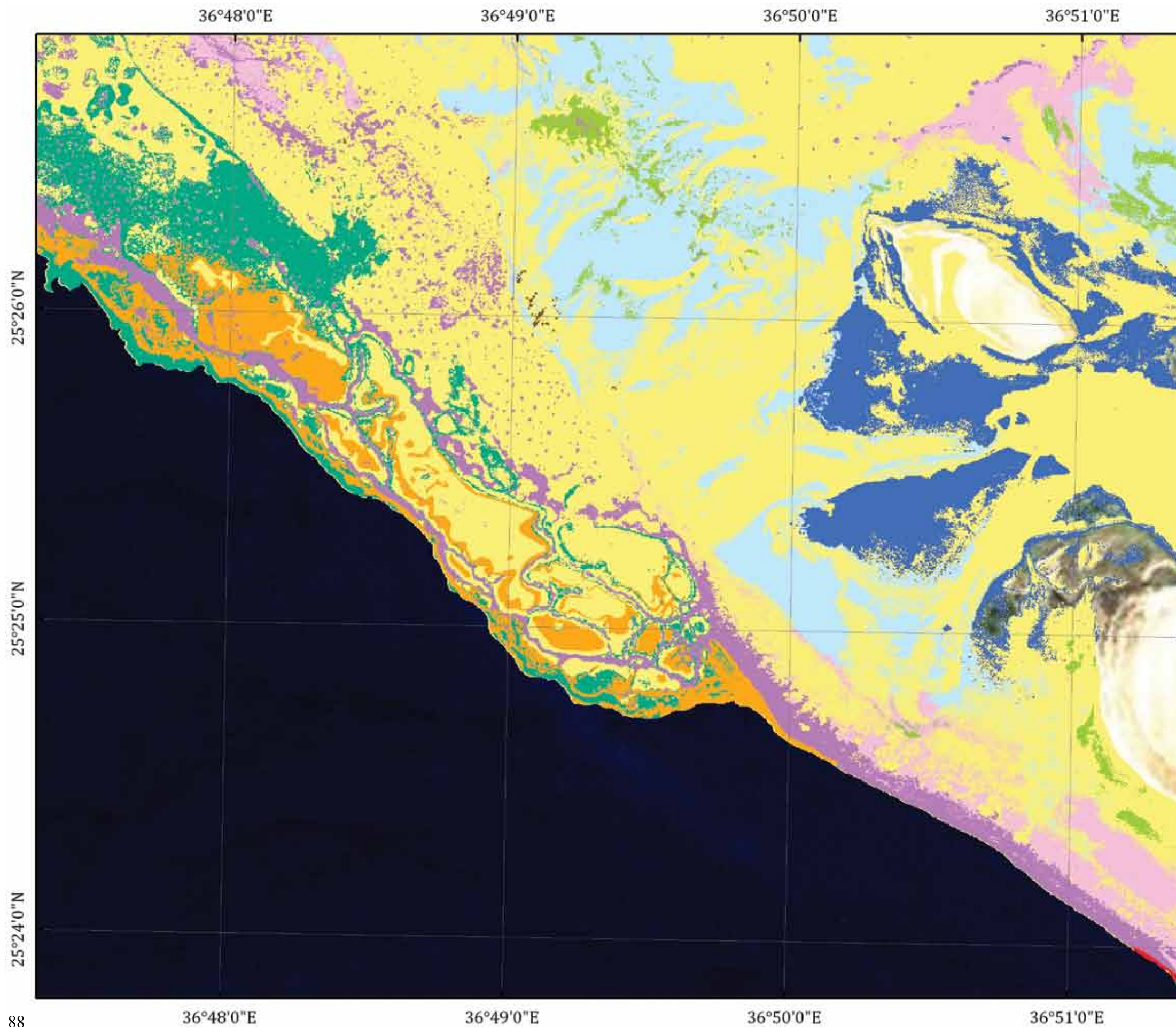
**Al Wajh Habitats**

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- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:24,000**

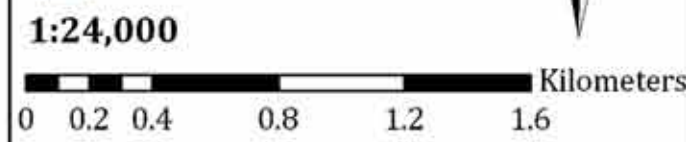
Kilometers

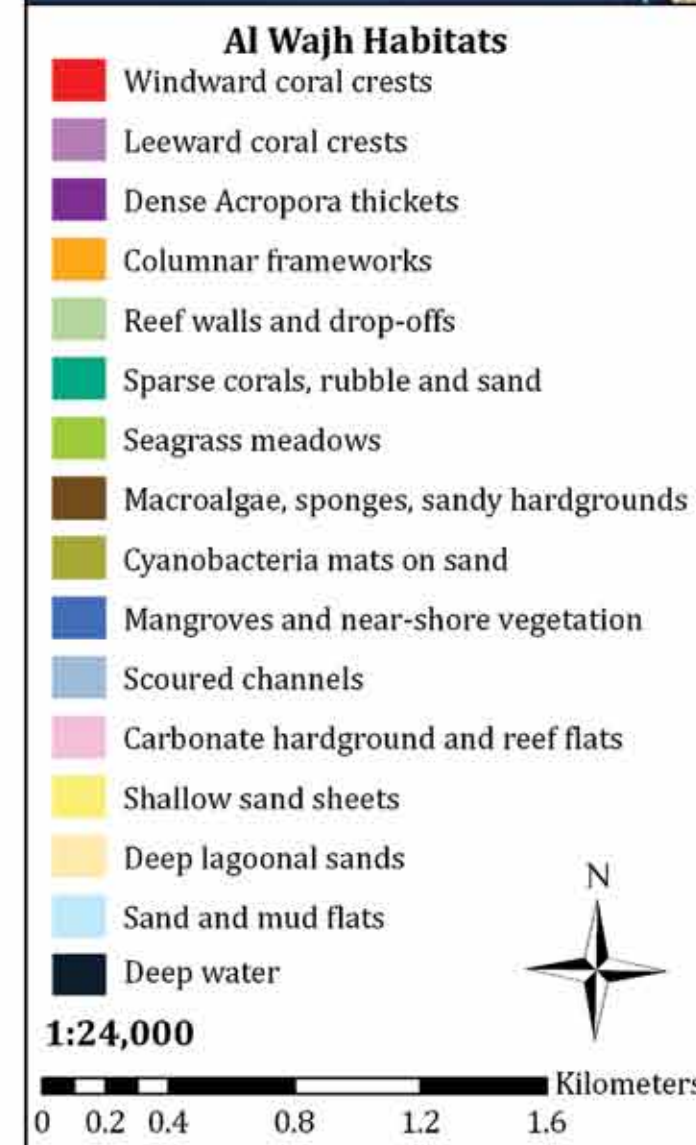
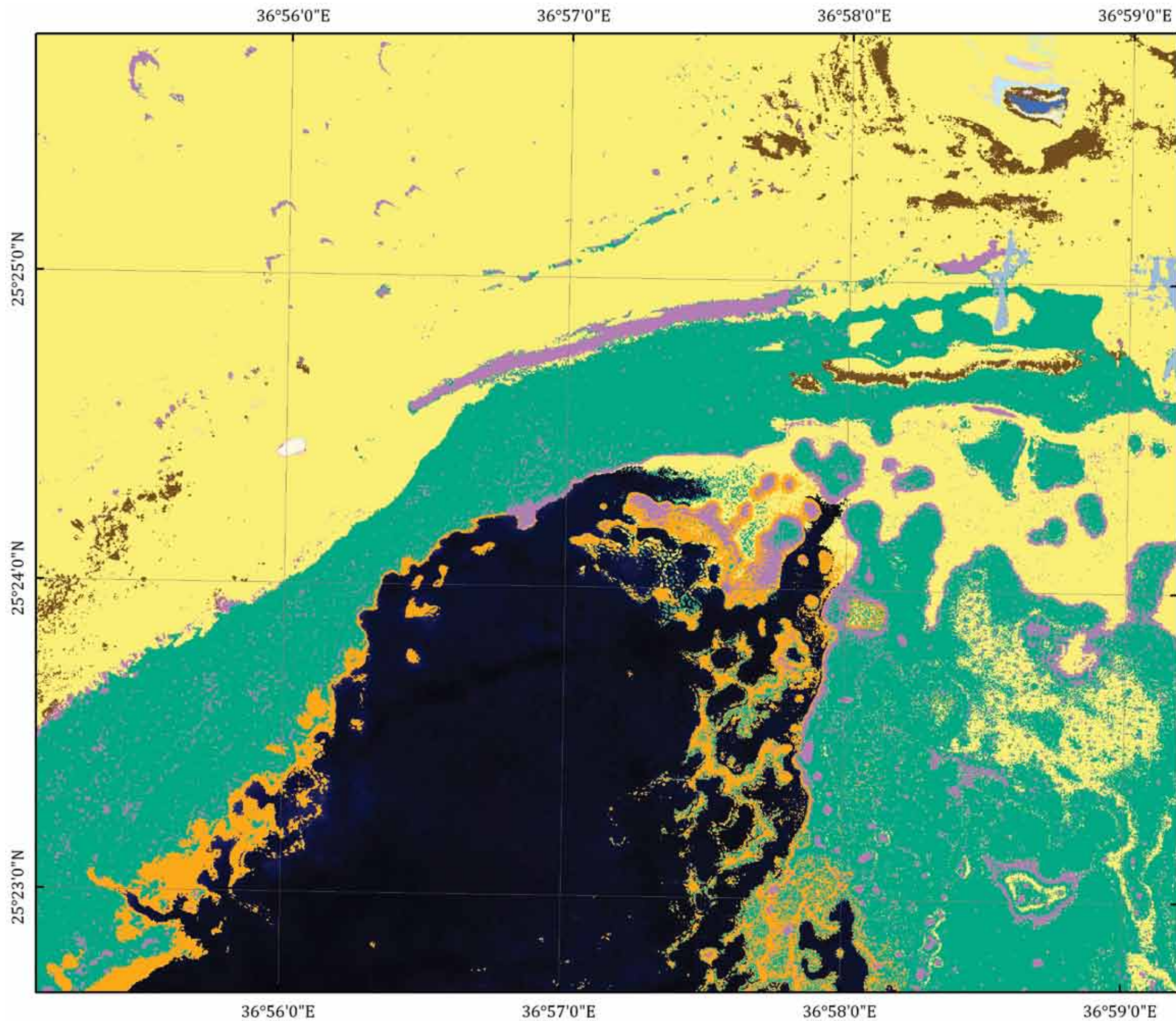


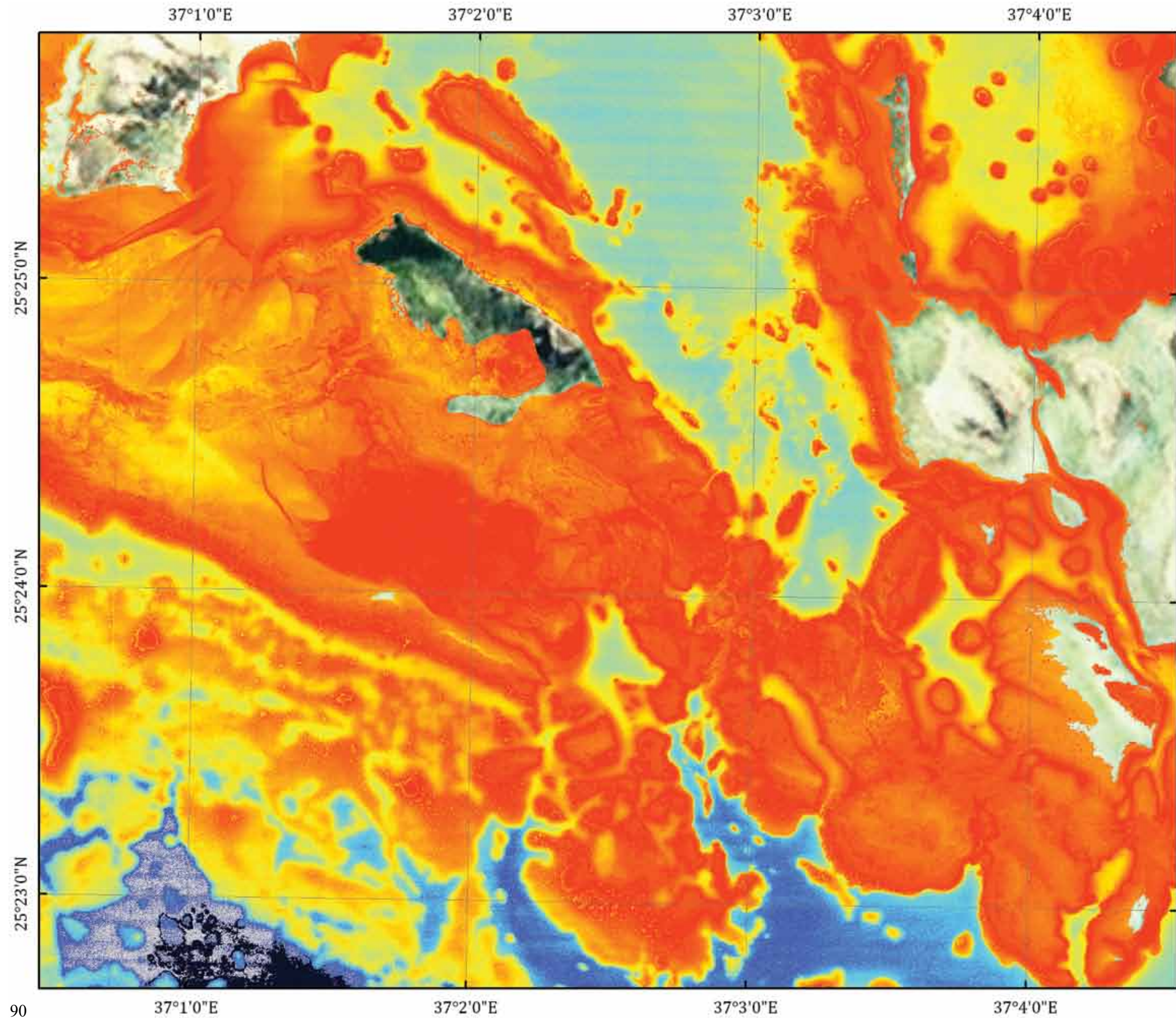


**Al Wajh Habitats**

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- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water





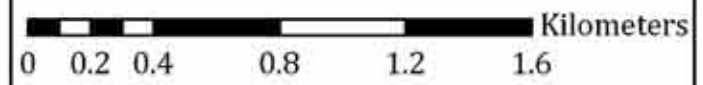


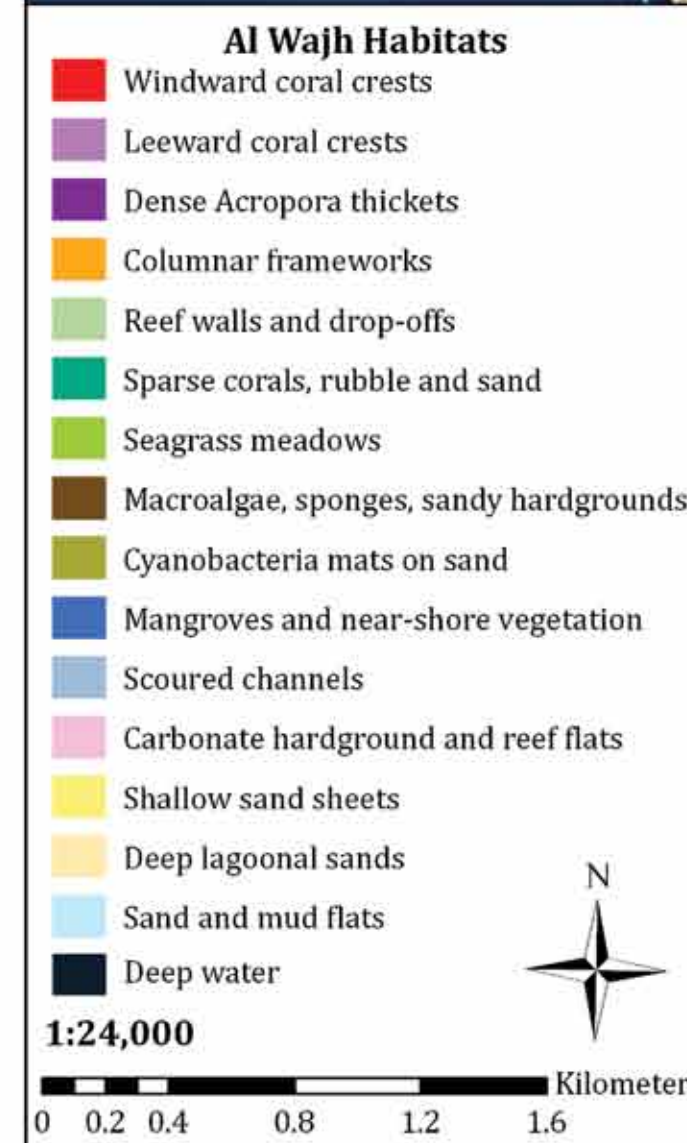
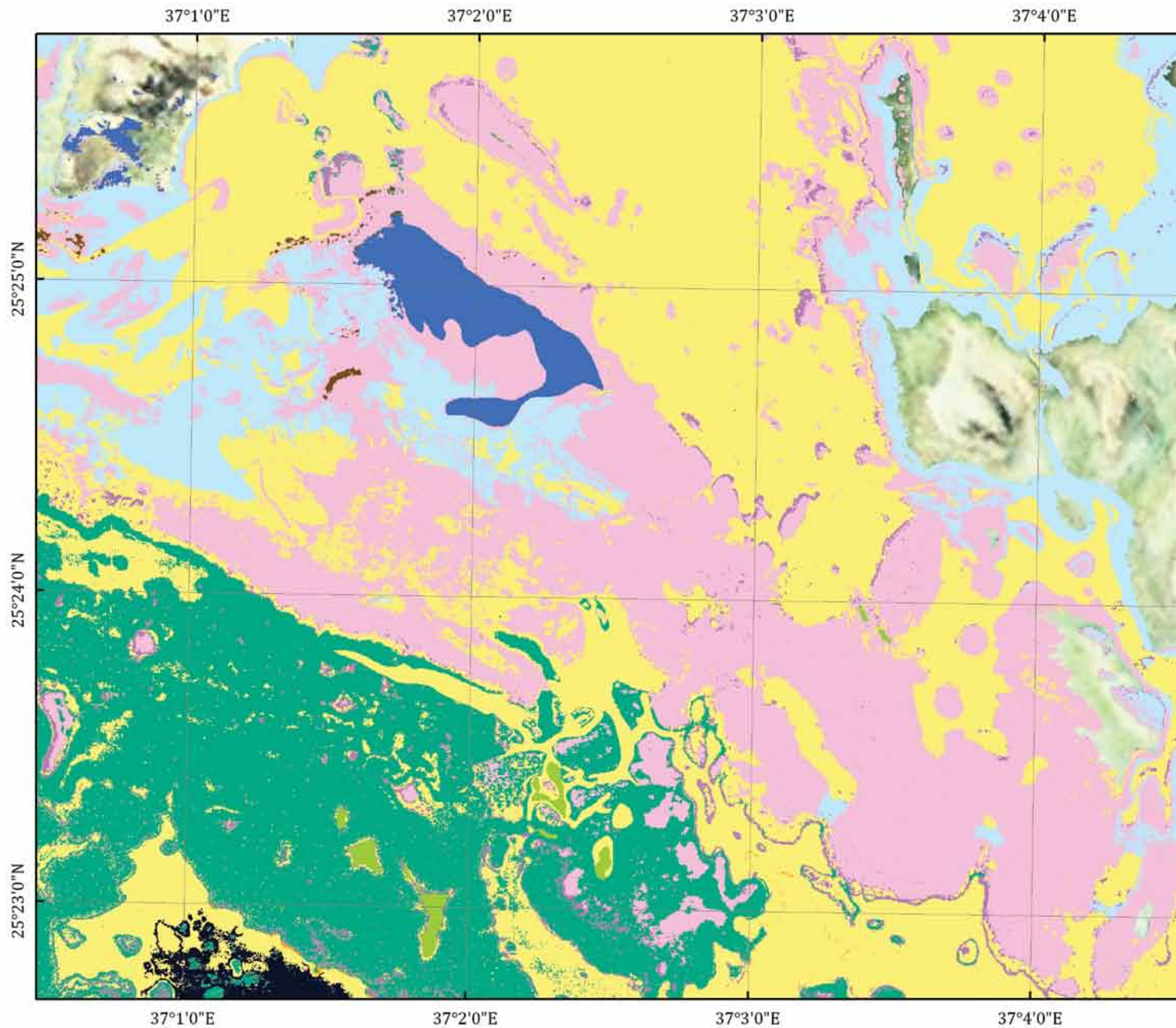
**Al Wajh Bathymetry**

**Depth, meters**

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

**1:24,000**



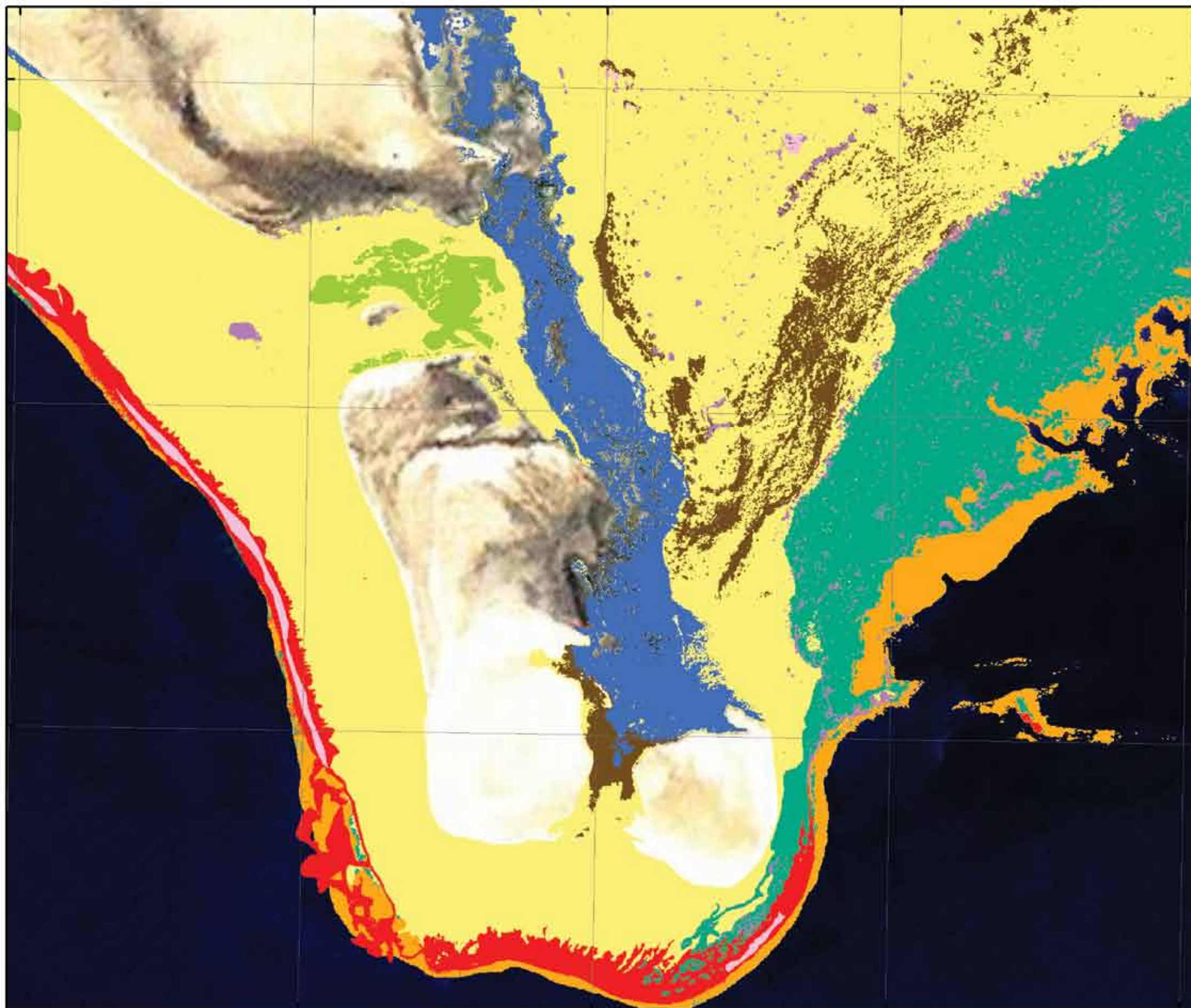


36°52'0"E 36°53'0"E 36°54'0"E 36°55'0"E 36°56'0"E

25°24'0"N

25°23'0"N

25°22'0"N



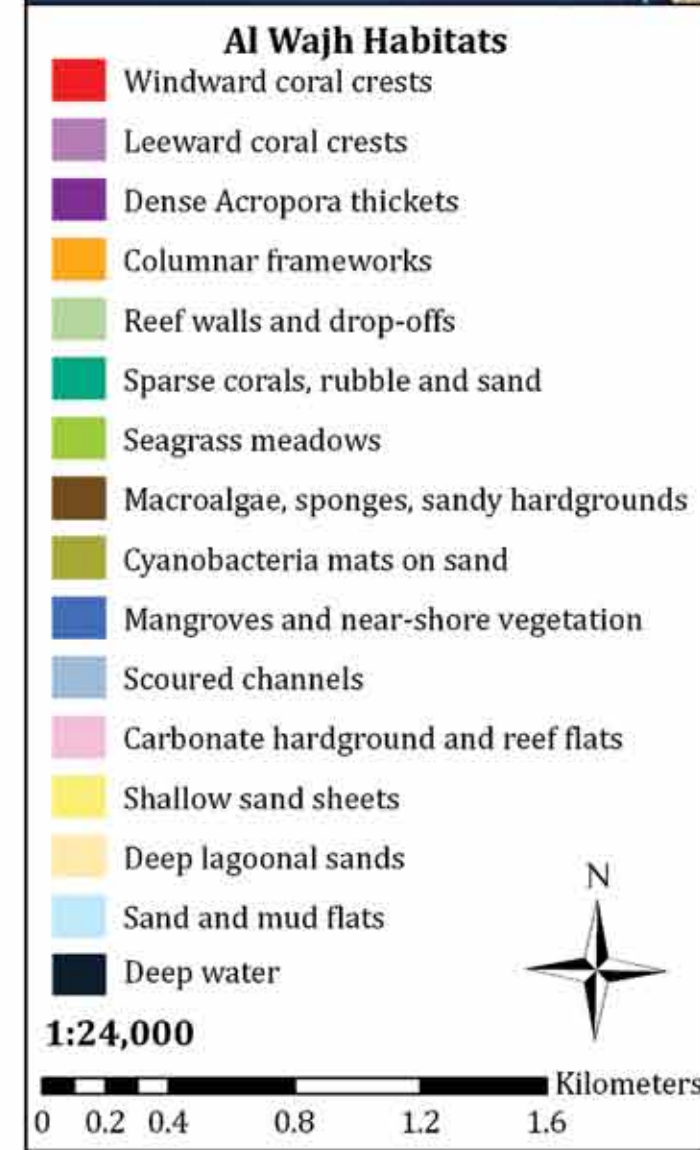
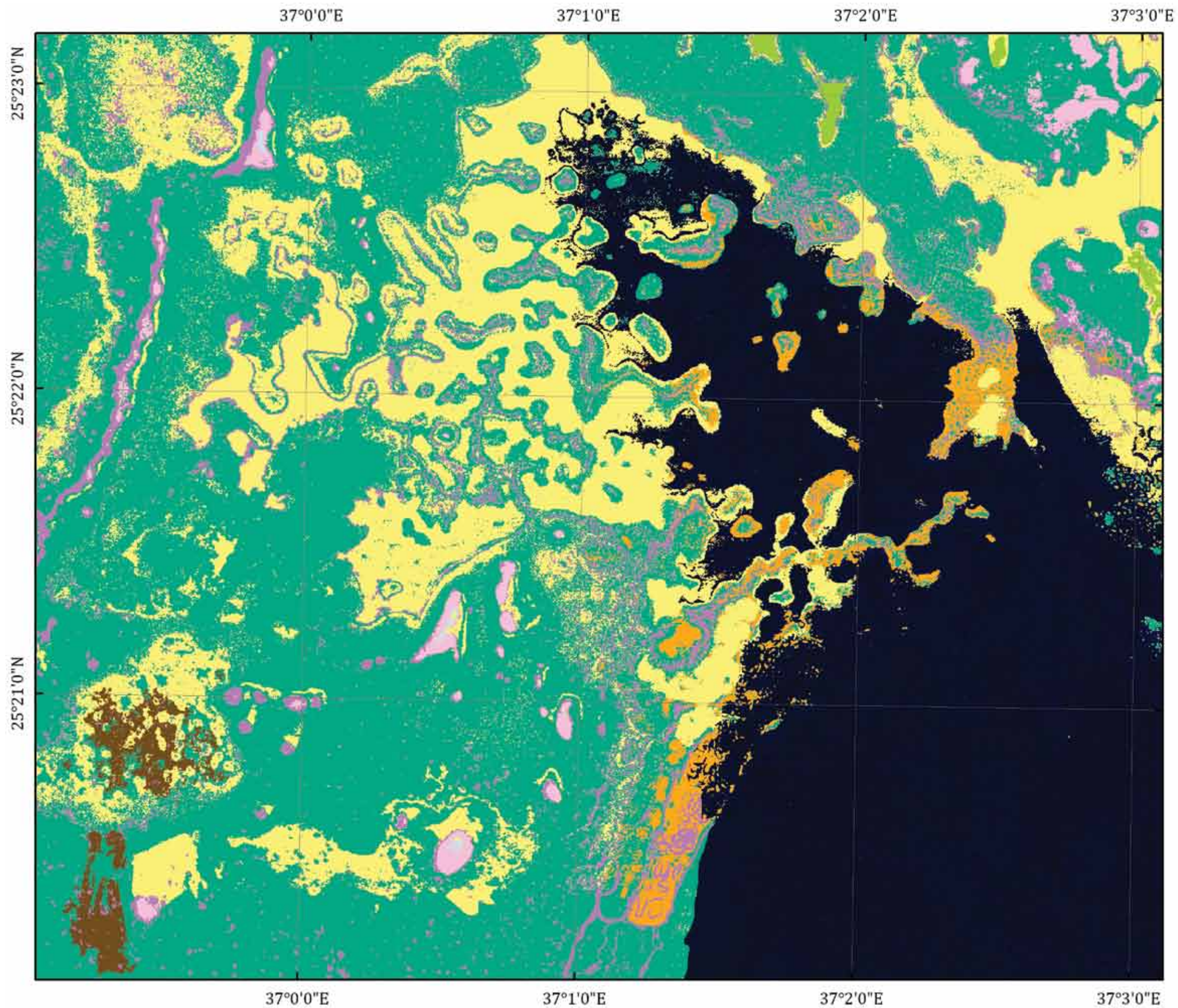
### Al Wajh Habitats

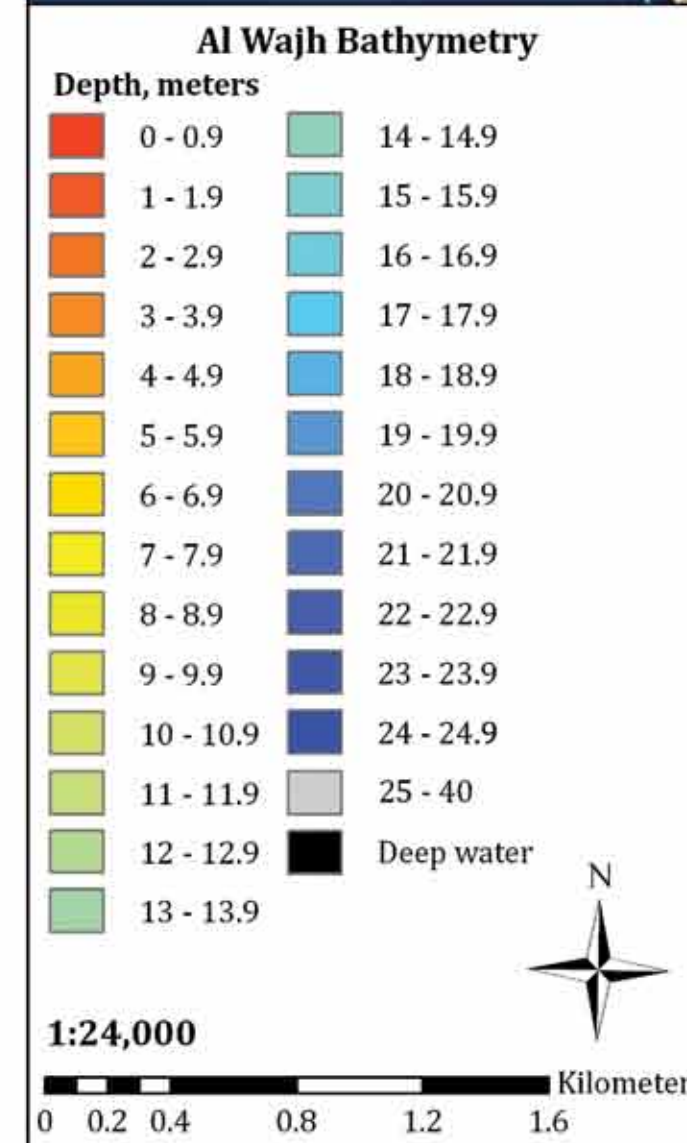
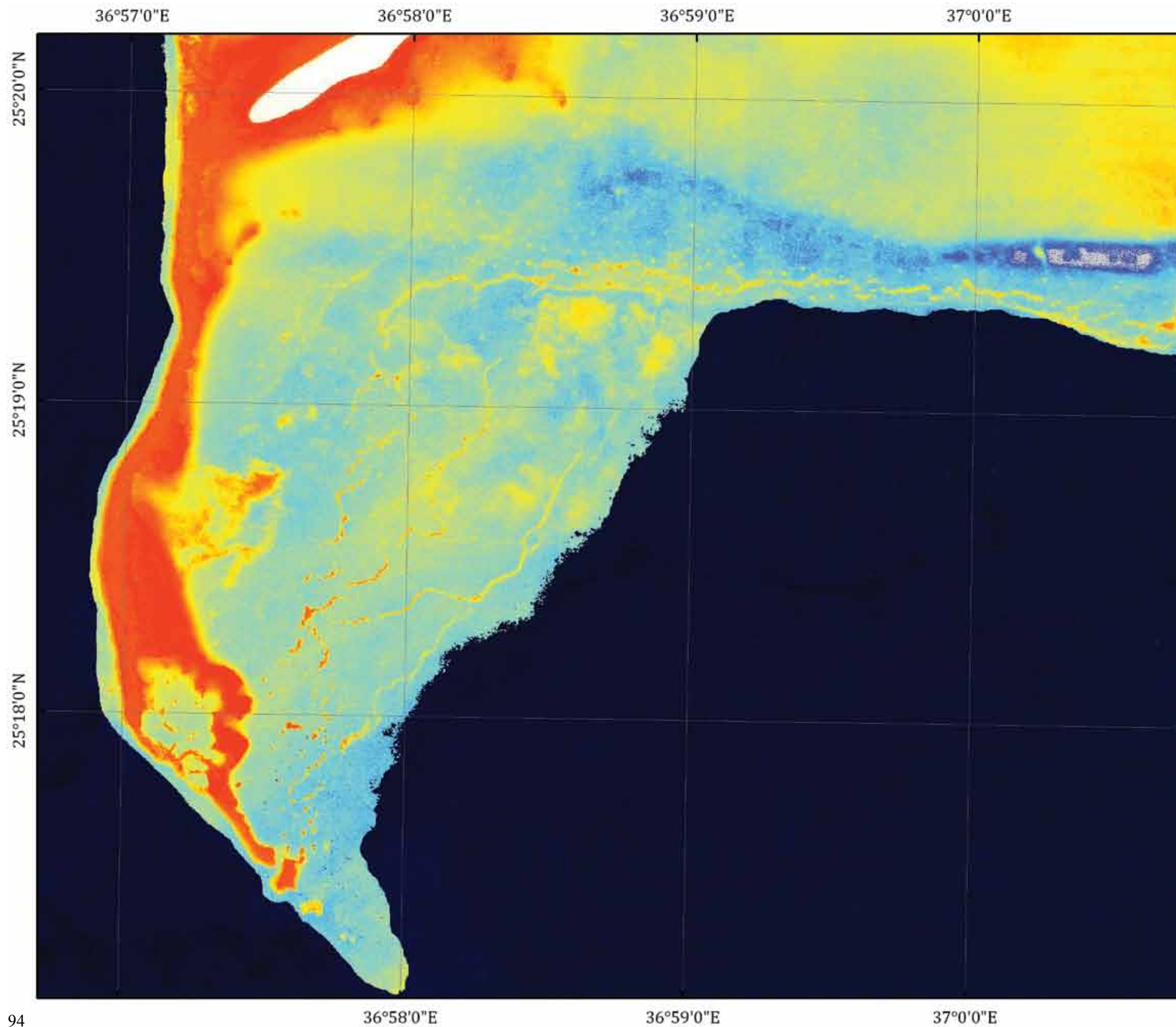
- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
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- Sand and mud flats
- Deep water

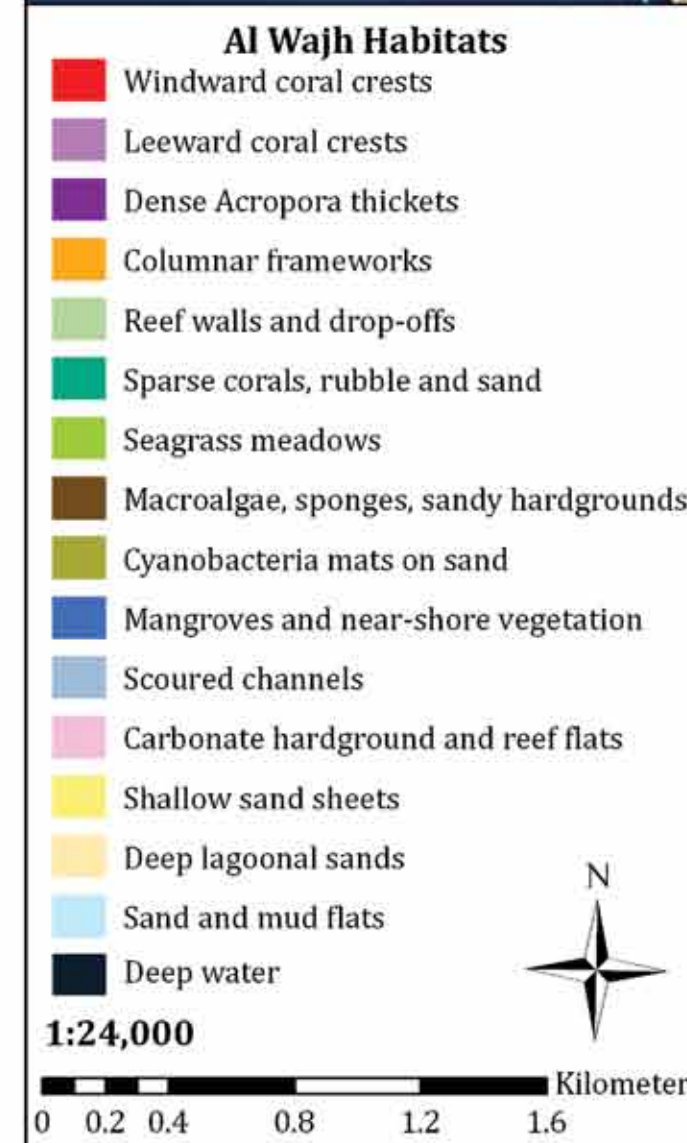
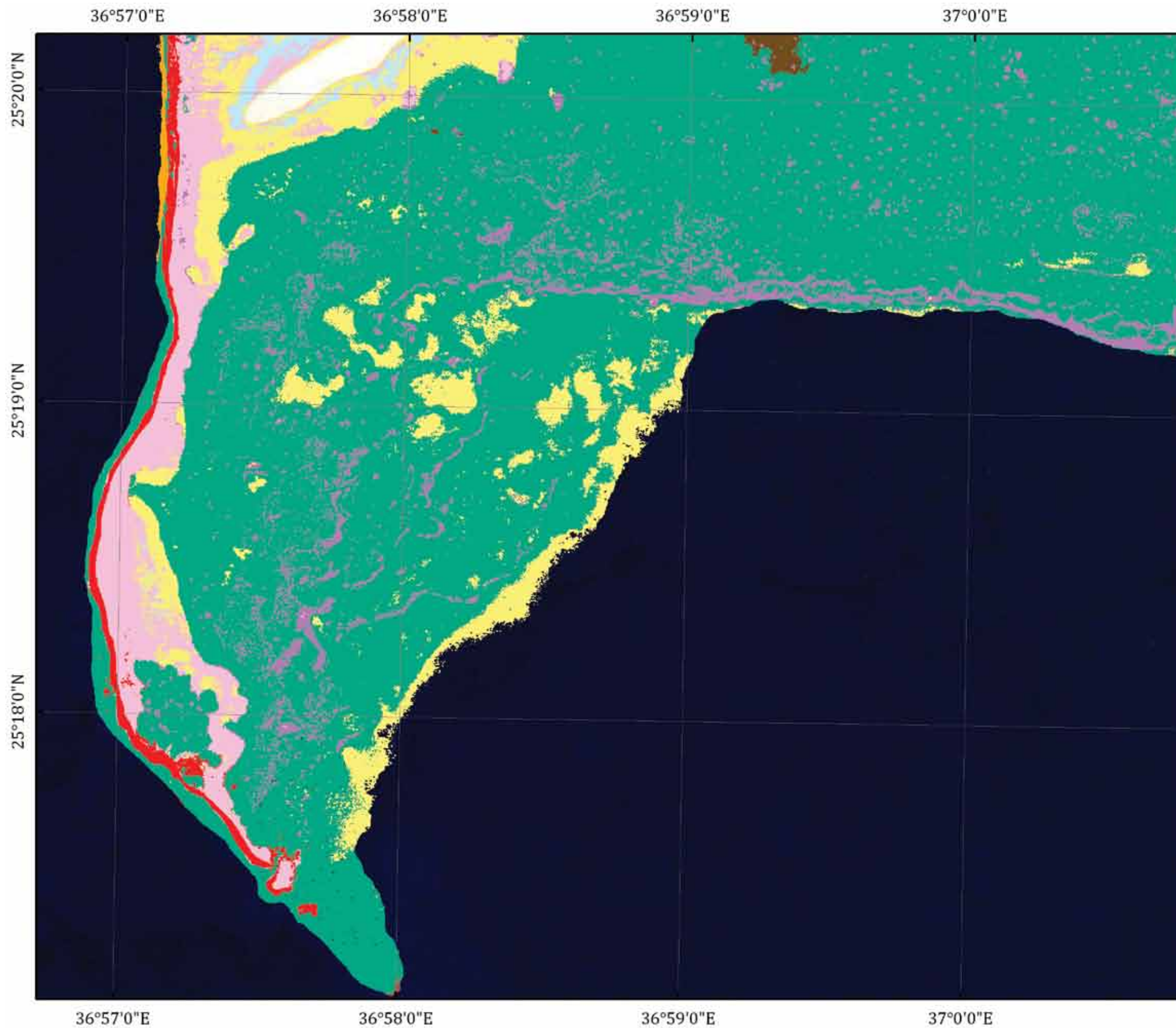
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36°53'0"E 36°54'0"E 36°55'0"E 36°56'0"E











Yanbu



## Yanbu

The Yanbu region, extending from Sharm al Khawr near Ra's al Jarbub in the north to Masturah in the south, covers a linear distance of about 160 km. The region contains extensive shallow coastal marine habitats and a complex offshore barrier reef system. The coastline consists of alluvial sand flats and low-lying hills that extend inland for more than 10 km, with salt marshes found in several locations in the intertidal zone. Yanbu's industrial city covers approximately 15 km of the coastline, occupying an area of 158 sq km. The city contains the largest oil shipping complex in the Red Sea, as well as more than 20 hydrocarbon, petrochemical and mineral facilities. The main reef system, termed the "little barrier reef," begins about 2-4 km off the coastline and is separated from the mainland by a major shipping channel.

Extensive mangrove habitats are found in the region, most of which are low-lying shrubs found in isolated patches, with best-developed thickets extending for over 11 km along the delta of Wadi Farrah, adjacent to the industrial city of Madinat Yanbu al-Sinaiyah. These mangrove stands are exclusively made up of the species *Avicennia marina*. Salt marsh vegetation occurred at the upper portion of the intertidal zone and further landward in areas subjected to occasional flooding by seawater. Salt marshes generally are characterized by a dry surface with muddy/sandy sediments. Shallow subtidal areas in protected nearshore environments are often colonized by seagrasses. Six seagrass species have been observed at Yanbu: *Halophila stipulacea*, *Halophila ovalis*, *Syringodium isoetifolium*, *Thalassia hemprichii*, *Cymodocea rotundata*, and *Halodule uninervis*.

Opposite page, left: Location of Yanbu. Source of basemap: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

Opposite page, top right: Two reefs meet in the northern Red Sea. Just below the waterline is the present-day reef that has grown over the past several thousand years. The raised platform is a fossil, Pleistocene reef, which has formed at a higher sealevel than today. Erosion has isolated a part of the fossil reef, seen as a mushroom-shaped rock to the right of the main reef structure. The massive rocks at the bottom of the exposure are the fossil reef, while some lagoonal sediments of a later reef-building episode rest on top.

Opposite page, bottom right: Reef flat community in front of Sh'as Sabah island. The reef flat is a hardground area interspersed with small sand-bottom pools and a shallow lagoon.



Massive *Porites lutea* colony surrounded by other soft and stony corals on the shallow (8 m depth) fore reef. The coral is over 2 m in diameter.

A vertical profile extending from the shore to deep water at Yanbu includes extensive shallow sand sheets; carbonate hardgrounds and reef flat close to shore; a leeward reef crest; and a columnar framework, which drops into a deep channel separating nearshore habitats from the barrier reef system. The barrier reef consists of a series of discontinuous columnar reef frameworks, shallow hardground and reef flat communities, windward reef crest, dense *Acropora* thickets, and a *Porites*-dominated reef slope. In some areas the reef community surrounds emergent land.



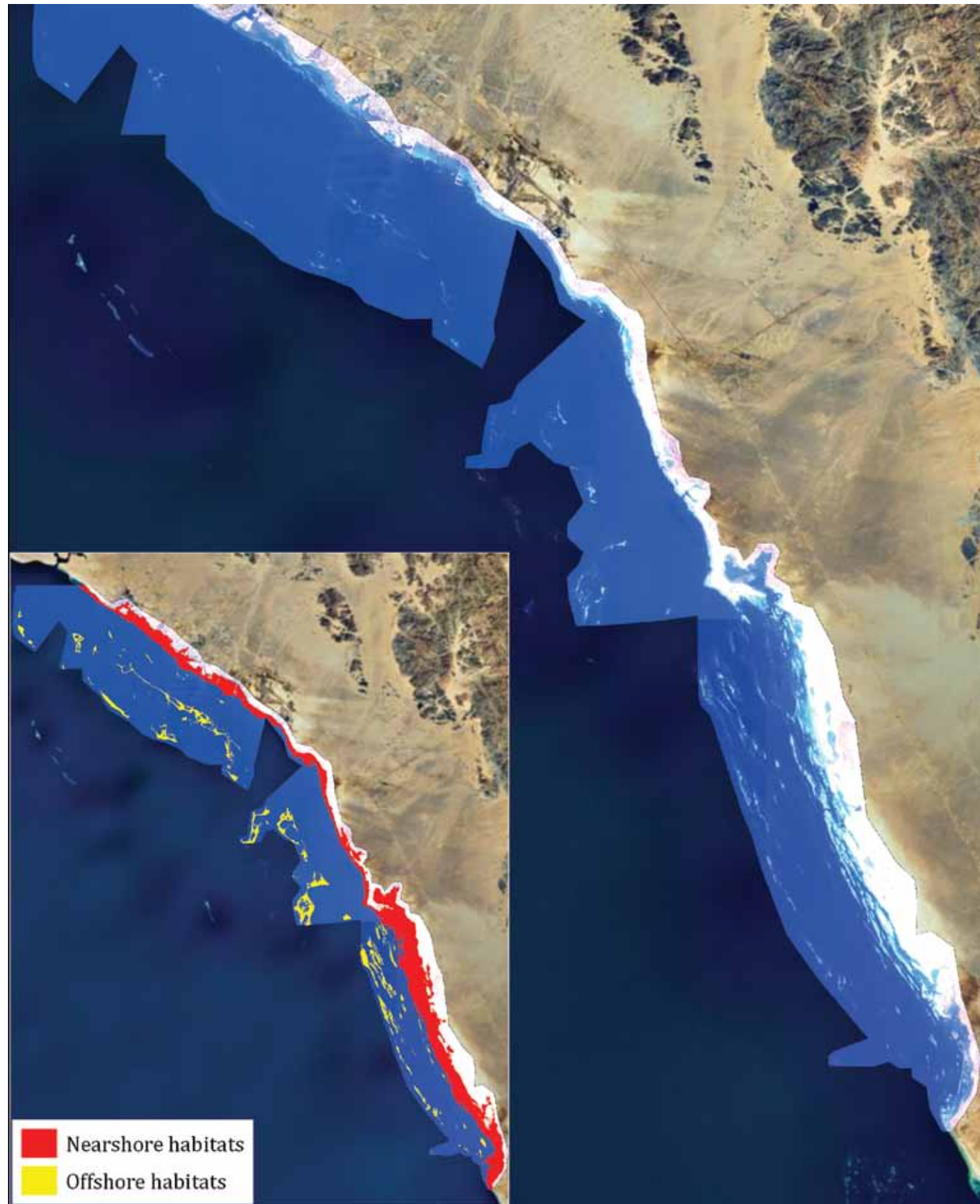
Leeward reef crest community with a large lobate colony of *Goniastrea*, and branching corals in the genus *Seriatopora*, *Acropora*, and *Pocillopora*.



Small branching acroporid corals that have colonized the *Porites* reef framework on a windward reef in the little barrier reef system of Yanbu.



Windward reef community dominated by branching *Pocillopora verrucosa* colonies and small colonies of *Acropora* spp.

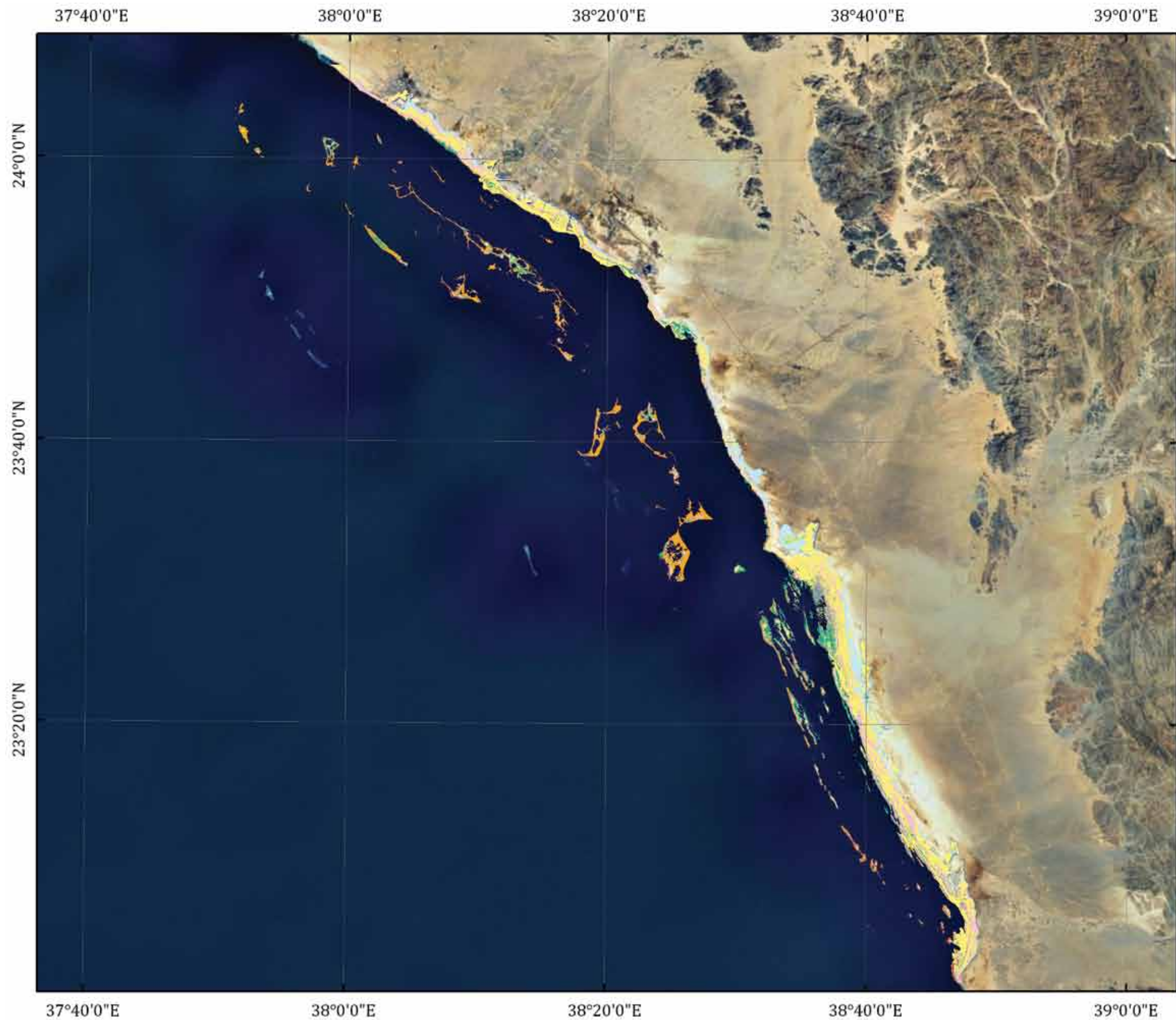


## Yanbu Imagery and Habitat Maps

Satellite imagery, bathymetry, and habitat maps for Yanbu are illustrated on pages 98-143. QuickBird multispectral satellite imagery of Yanbu (left), and a resulting habitat map for the same area (page 99) are shown at a scale of 1:525,000. The region is subdivided into three sections, with a locator map, bathymetric map, and habitat map shown at a scale of 1:200,000 for the north (pages 101-103), central (pages 117-119) and south (pages 133-135). Higher resolution habitat maps (1:24,000) and bathymetric maps for each section within Yanbu are shown after the 1:200,000 scale habitat maps. Bathymetric maps (1:24,000 scale) are shown on pages 108, 110, 112, 126, 128, 130, and 142 with habitat maps for the same area illustrated on the right (odd-numbered) page. Habitat maps start in the north and work progressively southward. These include habitats associated with the barrier reef and nearshore habitats. Source of terrestrial basemap imagery used in all habitat maps and bathymetric maps is: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

A total of 423 sq km were mapped and subdivided into 11 habitat classes with areas below 25 m depth (deepwater) depicted in dark blue. The aerial coverage of each habitat is presented in the table for nearshore areas, which extend from 0.5-1.5 km offshore (depicted in red in inset on the left), and offshore areas (depicted in yellow in the inset). The most extensive habitat type was shallow sand sheets, which made up over 43% of all marine habitats. Corals were found in six habitat types, covering an area of about 190 sq km. The majority of these reef habitats were represented by areas with very low coral cover, including carbonate hardgrounds and reef flats and sparse corals, rubble, and sand, which constituted over 110 sq km. Other soft-bottom habitats, excluding sand sheets, were dominated by sand and mud flats (48 sq km) with a limited amount of seagrass and mangrove habitat (2.5 sq km).

Yanbu Habitats	Total area (sq km)	% region total	Nearshore (sq km)	Offshore (sq km)
Reef walls and drop-offs	0.00	0.00	0.00	0.00
Windward coral crests	11.01	2.60	4.03	6.98
Leeward coral crests	14.23	3.40	14.20	0.03
Dense <i>Acropora</i> thickets	0.54	0.10	0.00	0.00
Columnar frameworks	49.26	11.60	0.60	48.66
Sparse corals, rubble, and sand	55.70	13.10	30.18	25.52
Seagrass meadows	0.94	0.20	0.93	0.01
Macroalgae, sponges, sandy hardgrounds	0.00	0.00	0.00	0.00
Cyanobacteria mats on sand	0.24	0.05	0.24	0.00
Mangroves and nearshore vegetation	1.45	0.30	1.45	0.00
Scoured channels	0.00	0.00	0.00	0.00
Carbonate hardground and reef flats	59.33	14.00	50.66	8.67
Shallow sand sheets	183.32	44.40	175.14	8.18
Deep lagoonal sands	0.00	0.00	0.00	0.00
Sand and mud flats	47.56	11.20	47.56	0.00
<b>TOTAL AREA MAPPED</b>	<b>424</b>	<b>100</b>	<b>325</b>	<b>99</b>



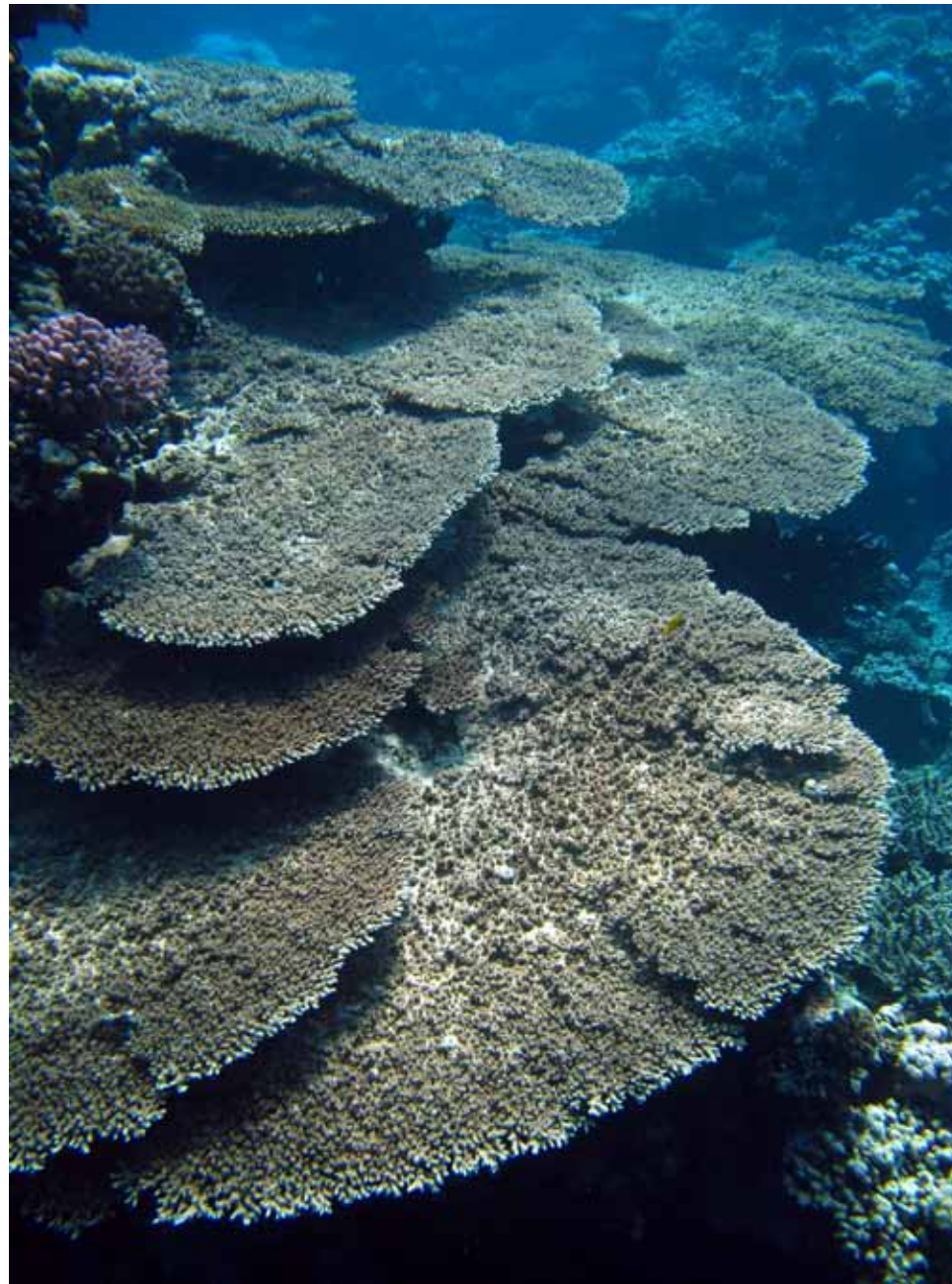
**Yanbu Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
- Seagrass meadows
- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water



**1:525,000**





Extensive thickets of branching acroporids and table acroporids are found on the offshore barrier reef in shallow water (3-8 m depth). Table acroporids like the one shown above (*Acropora cytherea*) may form a series of overlapping shingles that are several meters in diameter and height.



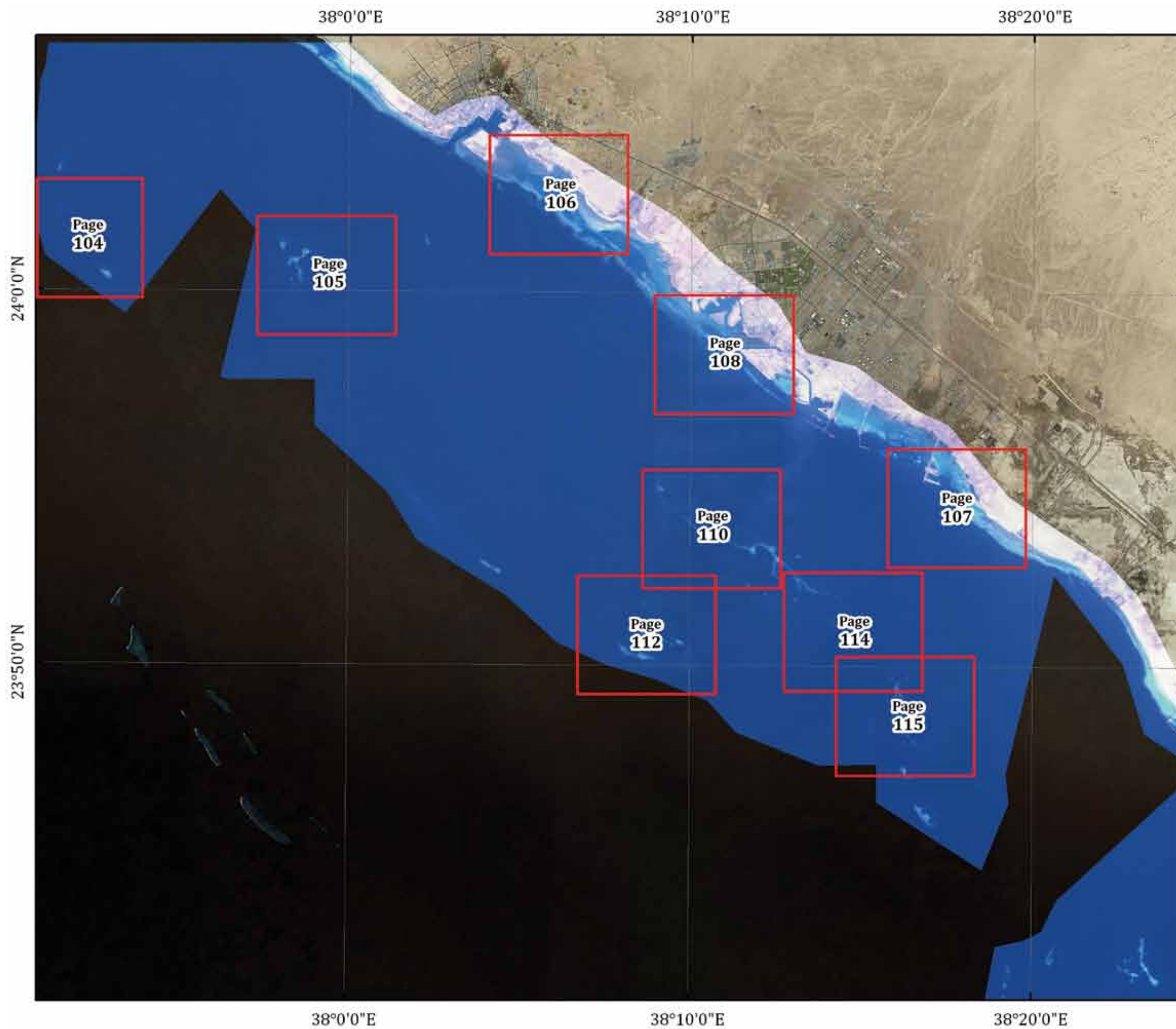
Shallow reef crest and fore reef communities (1-3 m depth) in protected environments had high cover of small branching corals in the Genus *Acropora* and *Pocillopora* that had colonized an underlying dead *Porites* framework.



While the framework at mid-depths (5-15 m depth) on offshore reefs was dominated by large colonies of *Acropora* and *Porites*, nearshore reefs had fewer large colonies of these species and a predominance of small faviid corals, including *Goniastrea* and *Favia*, small digitate, branching and tabular acroporids, and small colonies of *Pocillopora*, intermixed with dead corals.



Unusually large living colonies of *Porites lutea*, which formed lobate or columnar colonies, were found in shallow water on the offshore barrier reef. On nearshore reefs, most large colonies had extensive areas of partial mortality, and dead skeletons were colonized by other organisms.



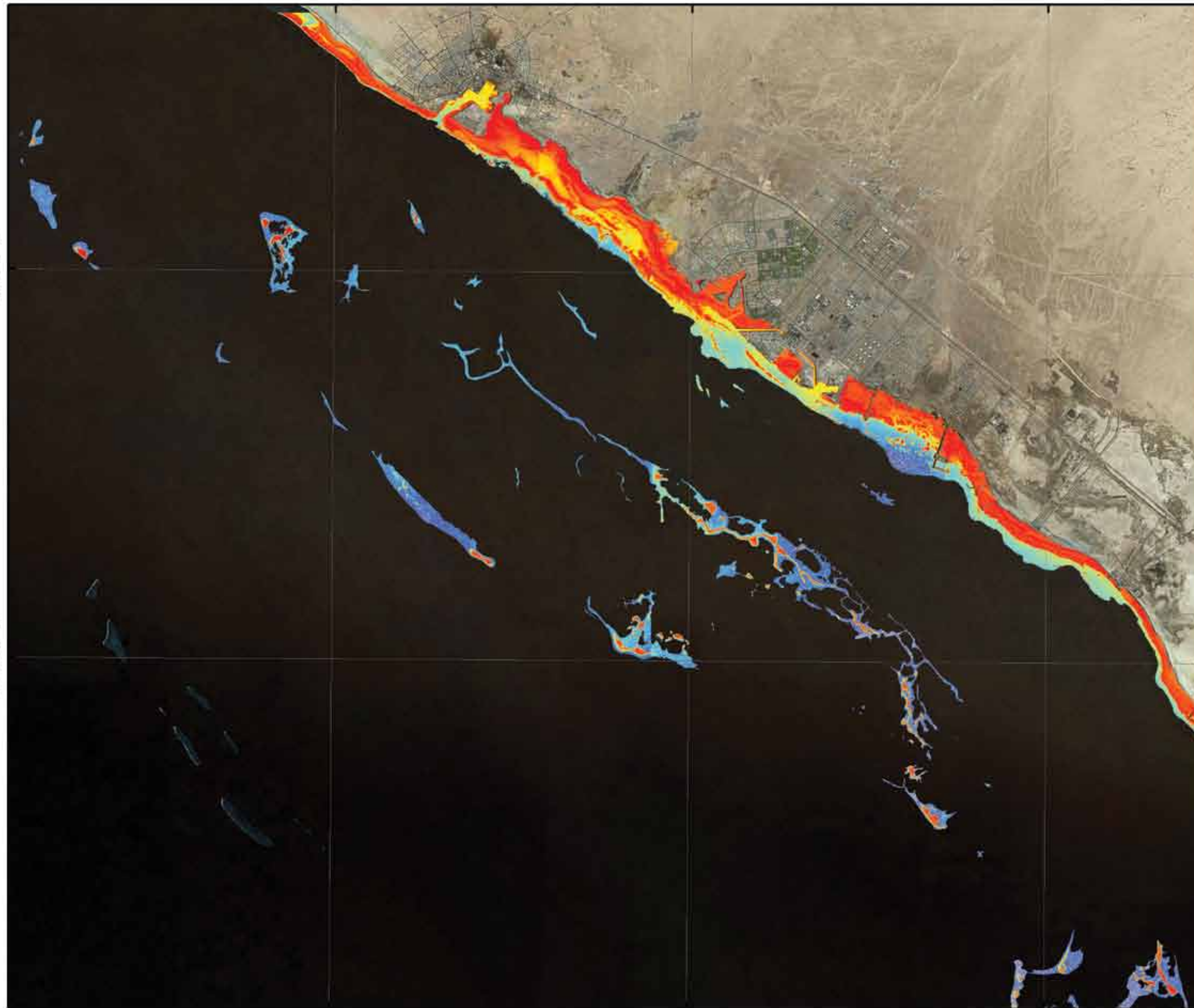
38°0'0"E

38°10'0"E

38°20'0"E

24°0'0"N

23°50'0"N



### Yanbu Bathymetry

Depth, meters

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

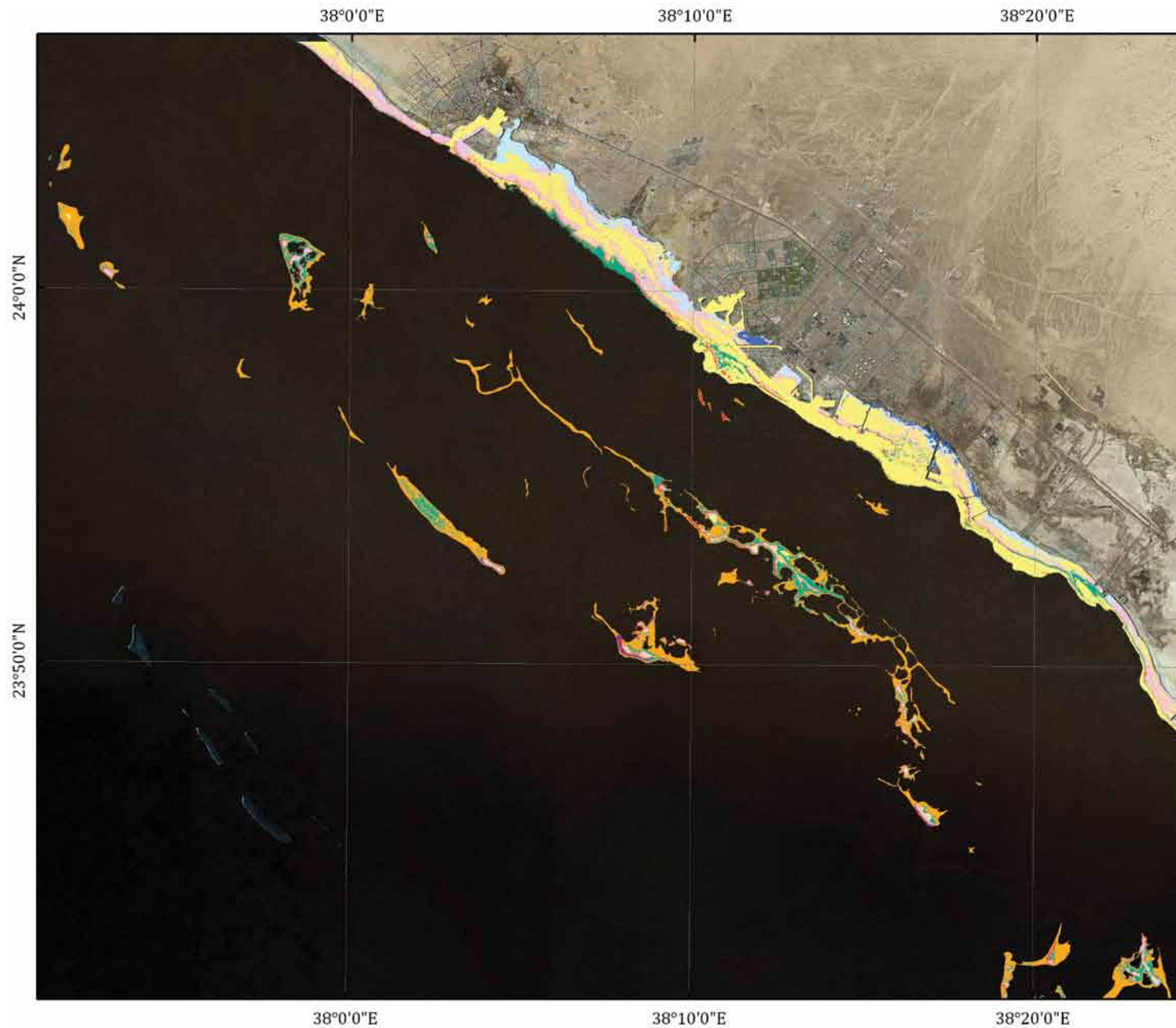
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38°0'0"E

38°10'0"E

38°20'0"E



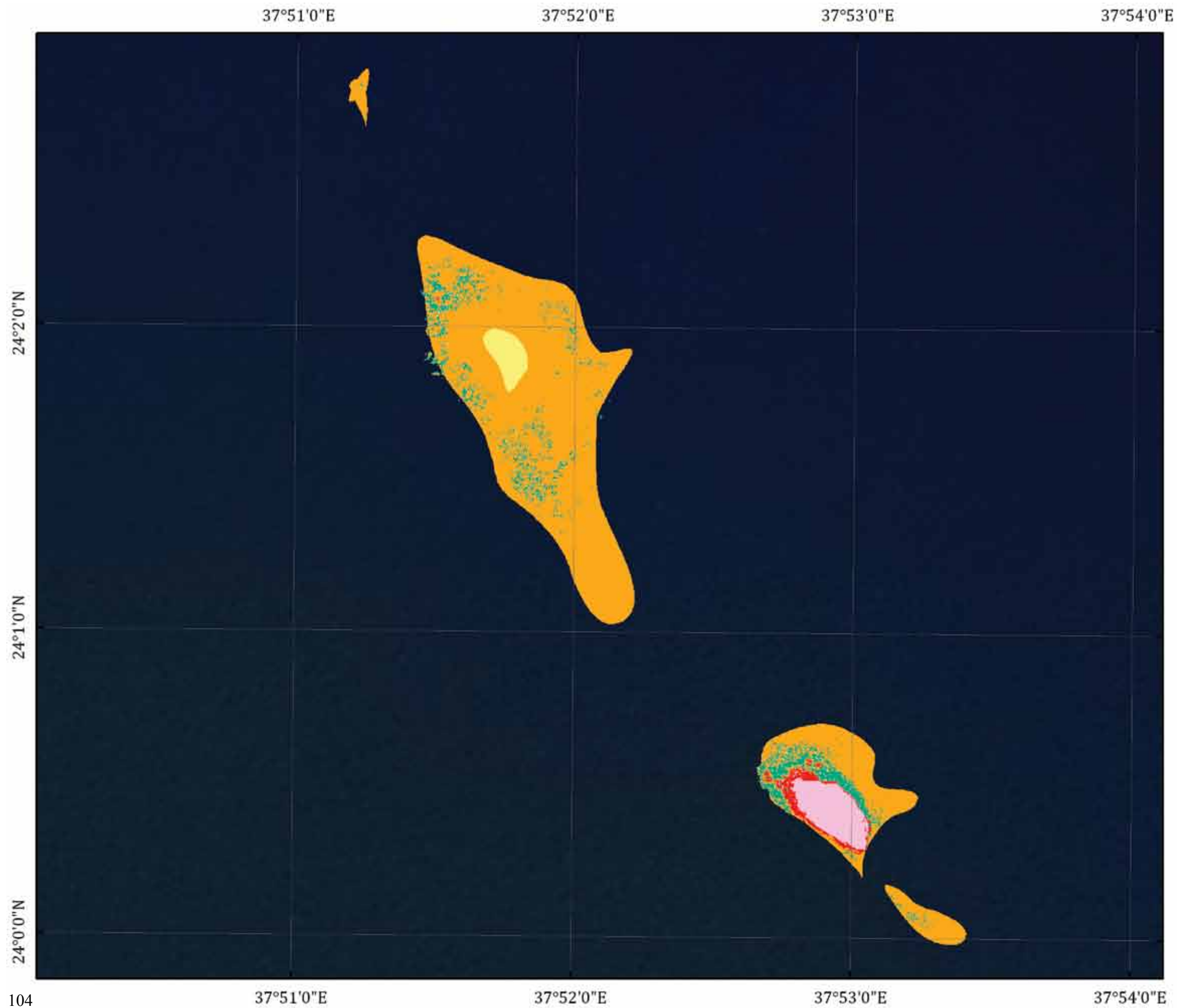
**Yanbu Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
- Seagrass meadows
- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water

**1:200,000**





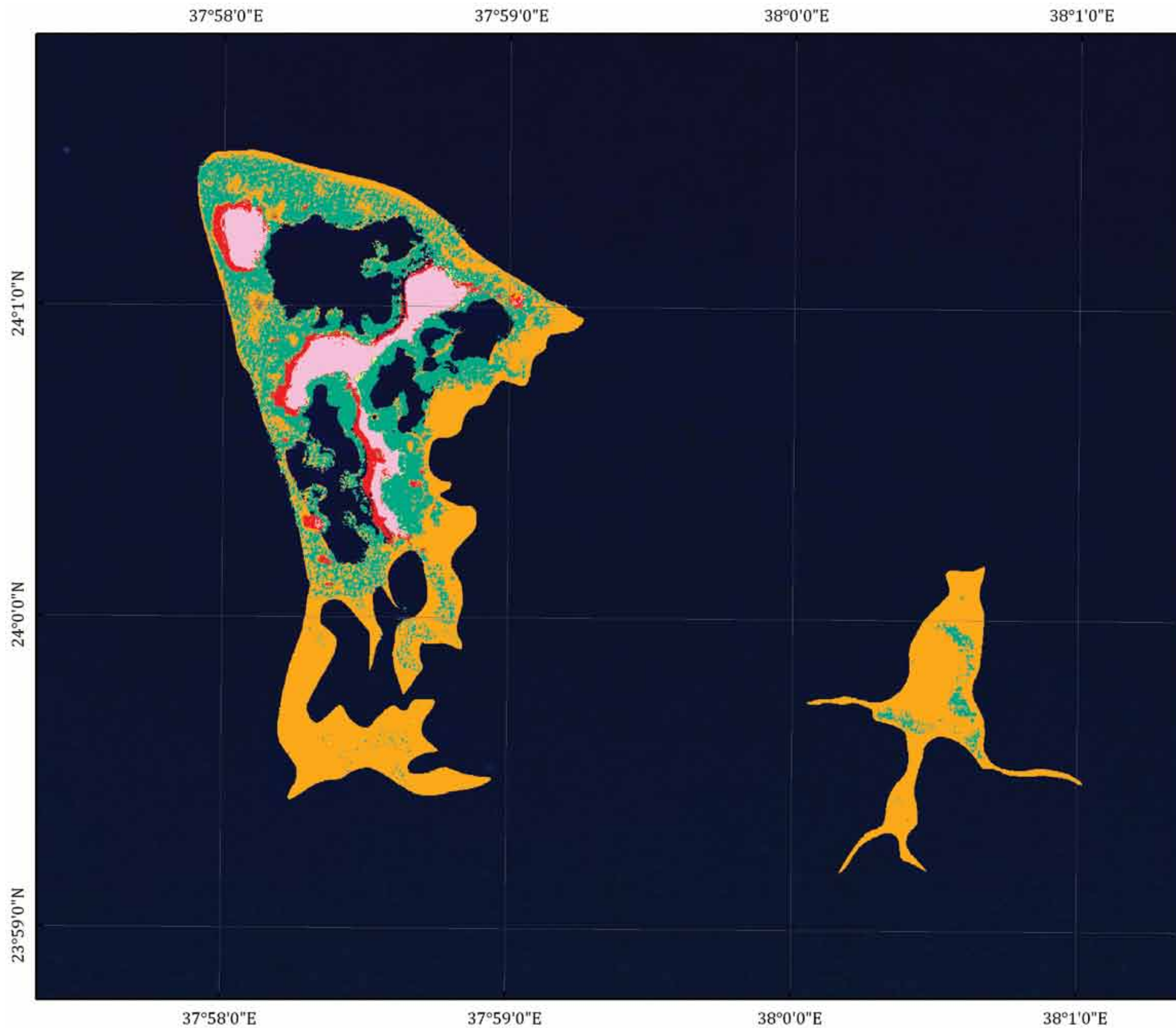


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1:24,000



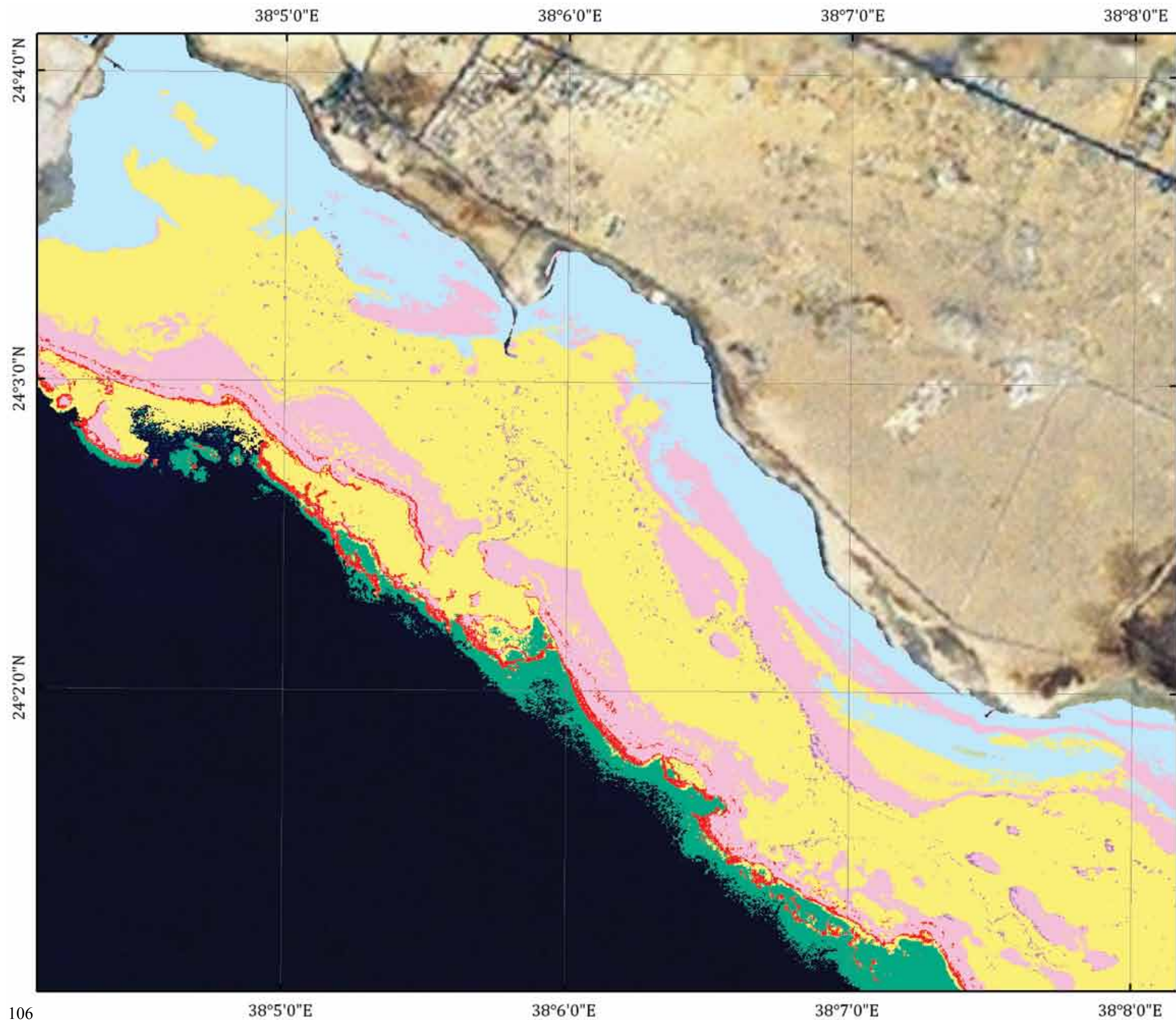


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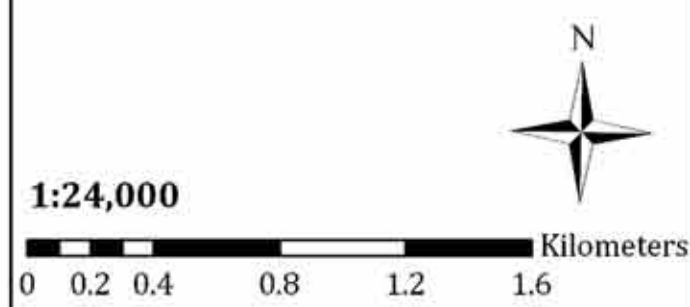
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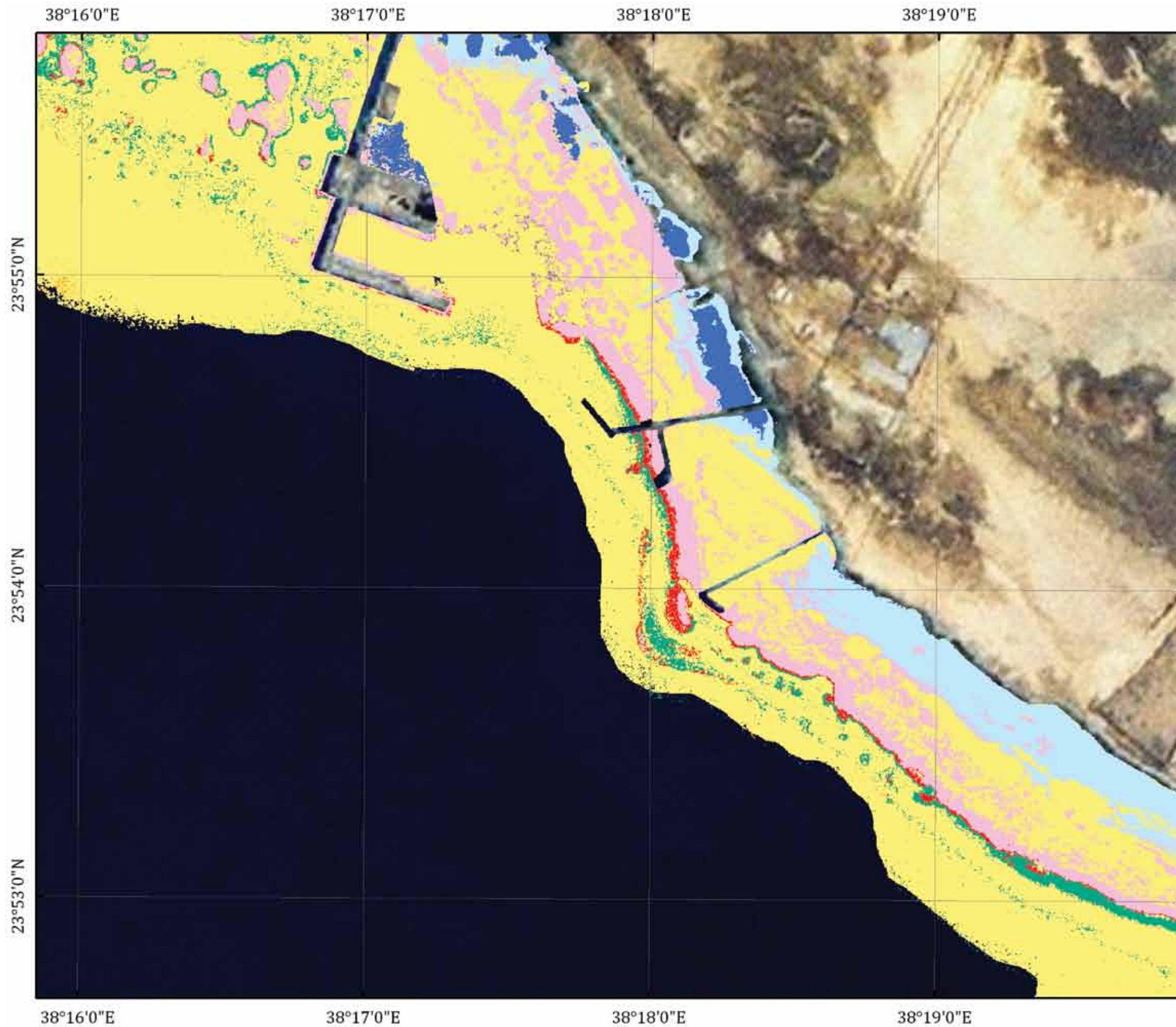




**Yanbu Habitats**

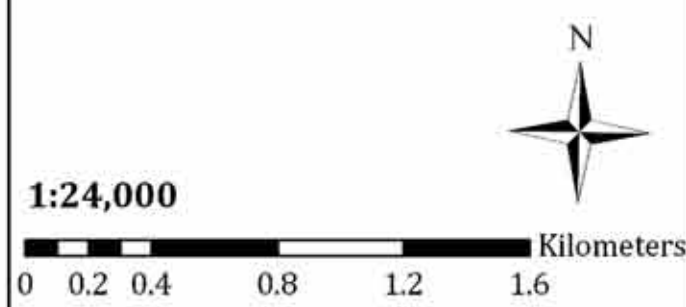
- Windward coral crests
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- Sand and mud flats
- Deep water

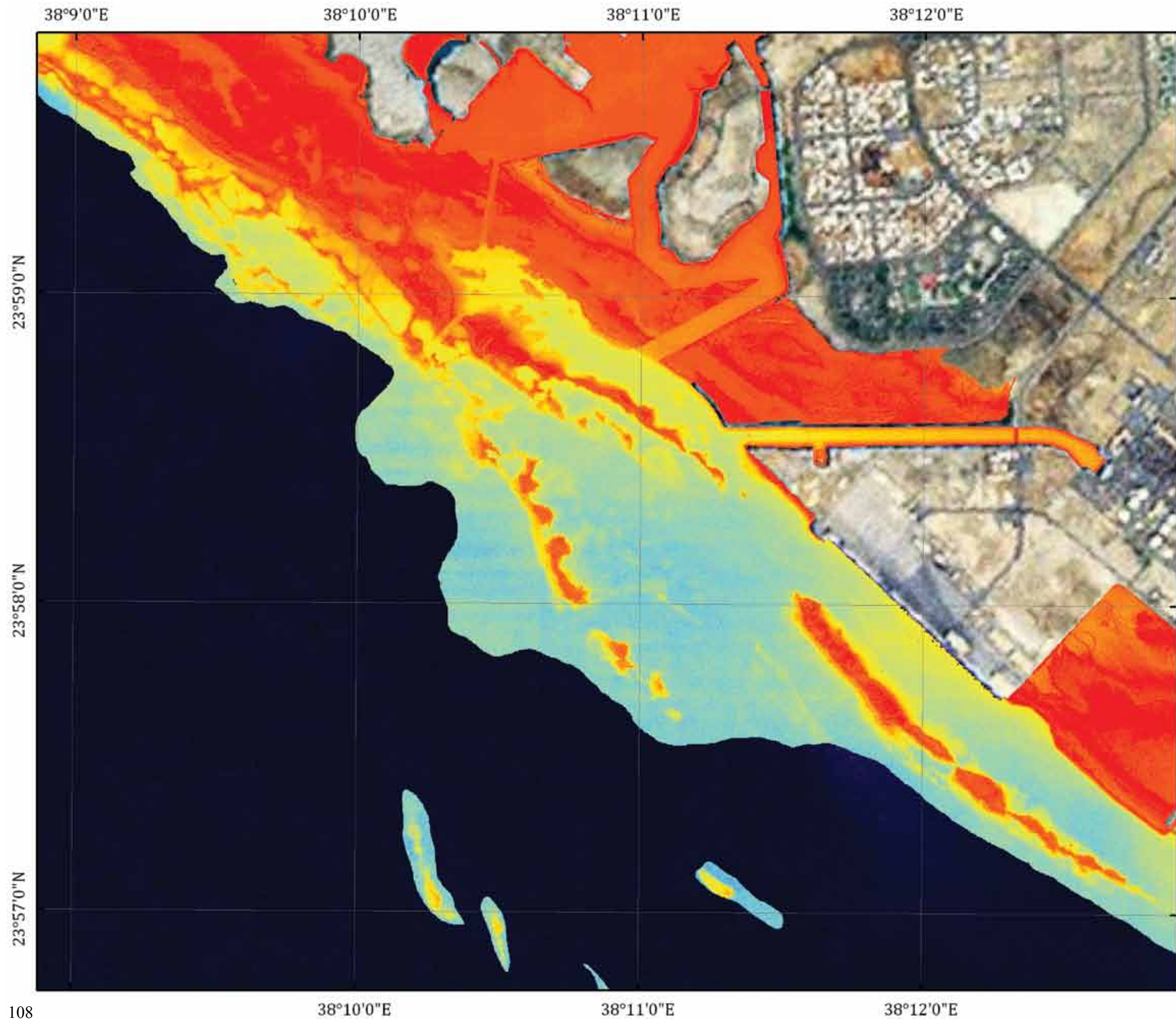




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- Sand and mud flats
- Deep water



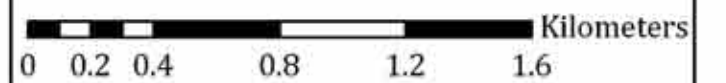


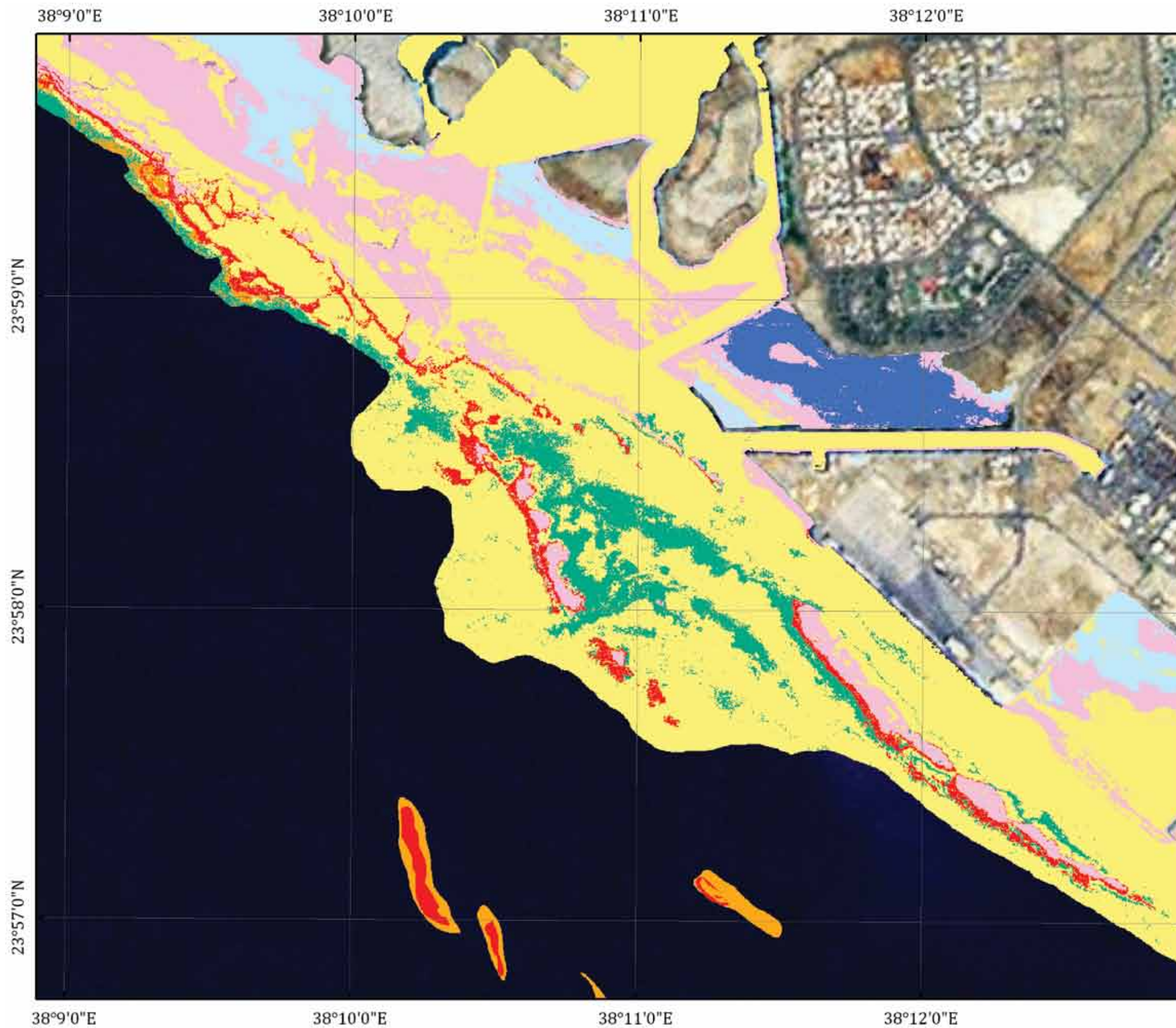
**Yanbu Bathymetry**

Depth, meters

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

**1:24,000**



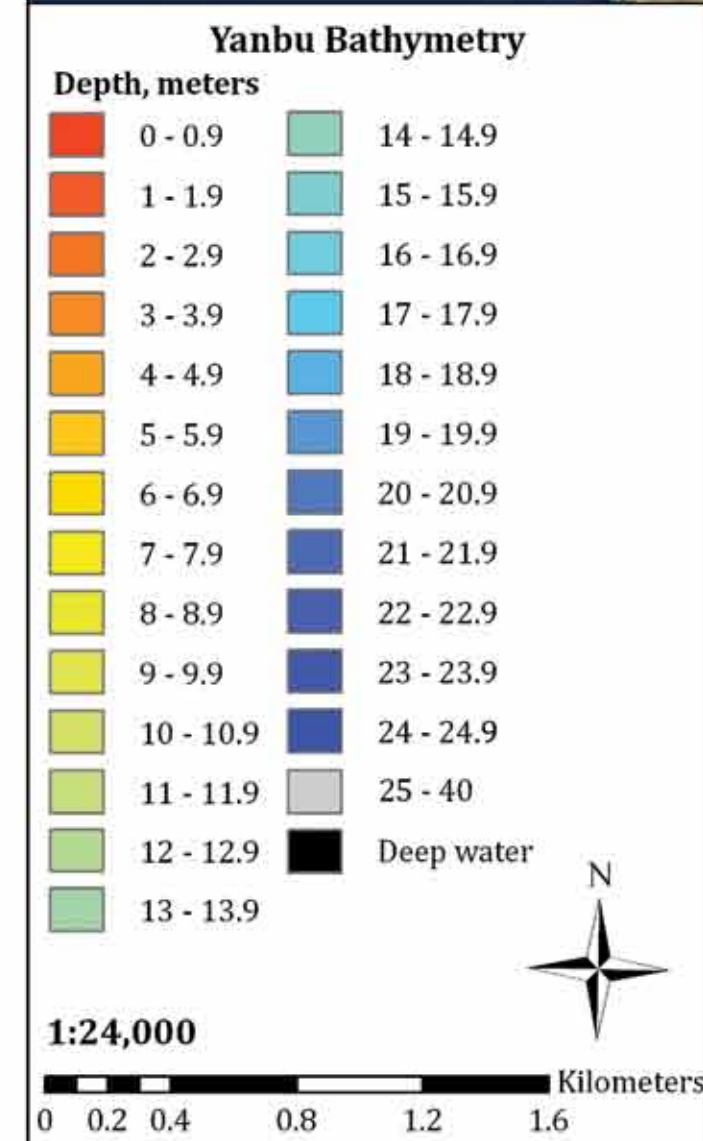
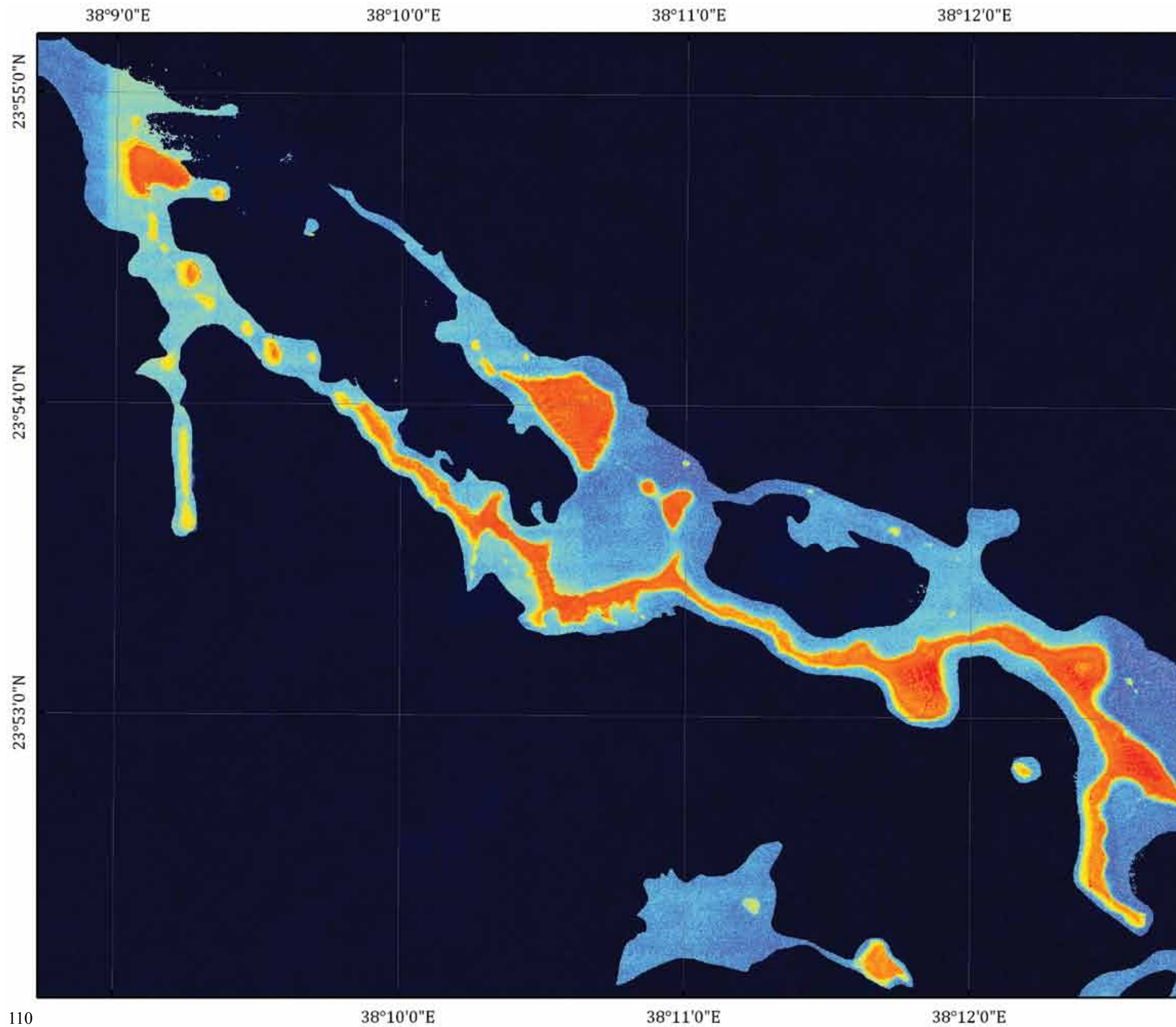


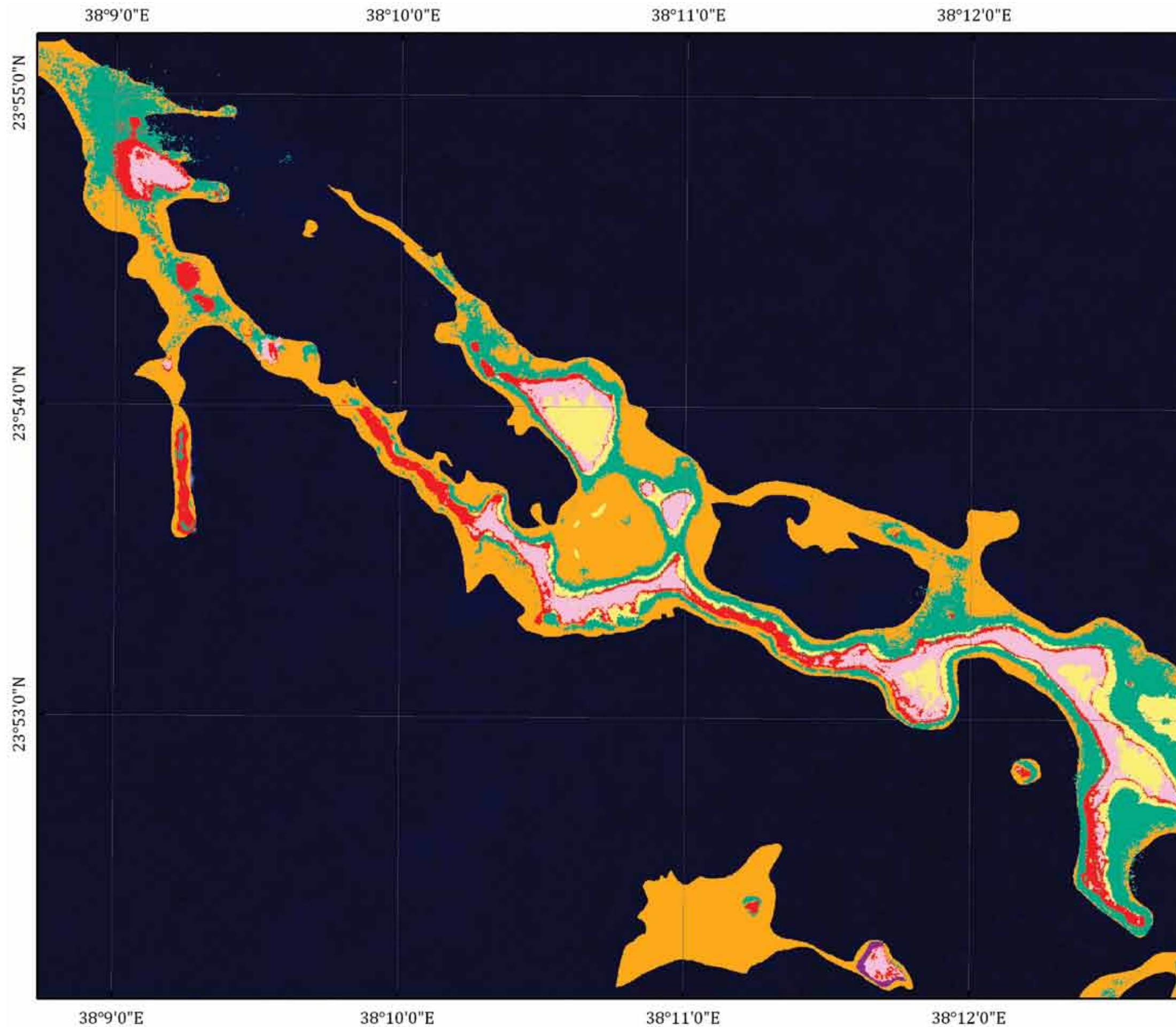
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1:24,000





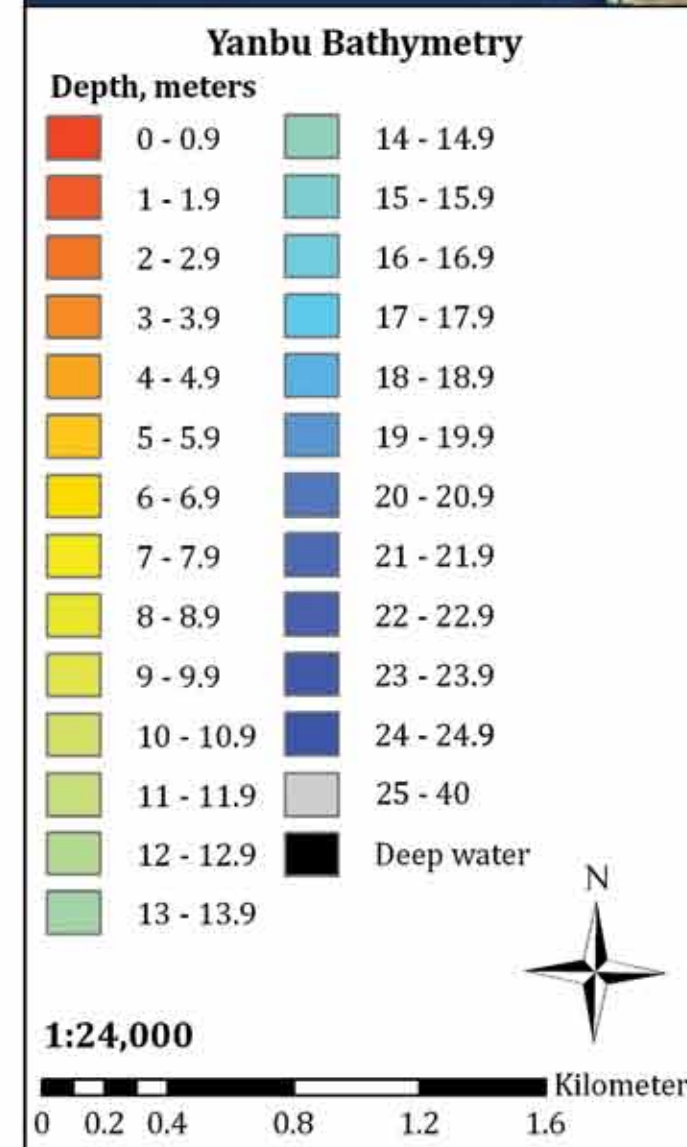
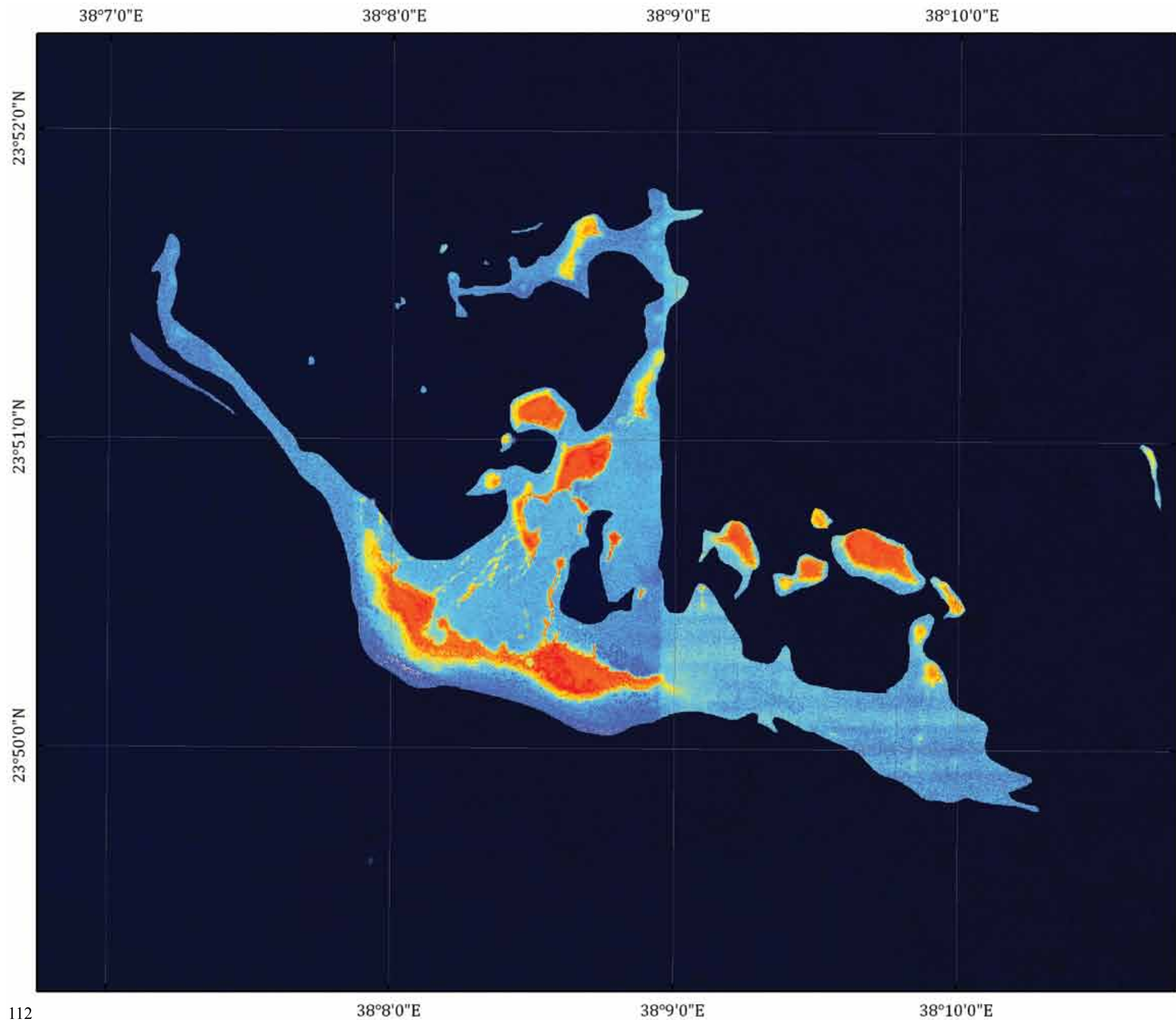


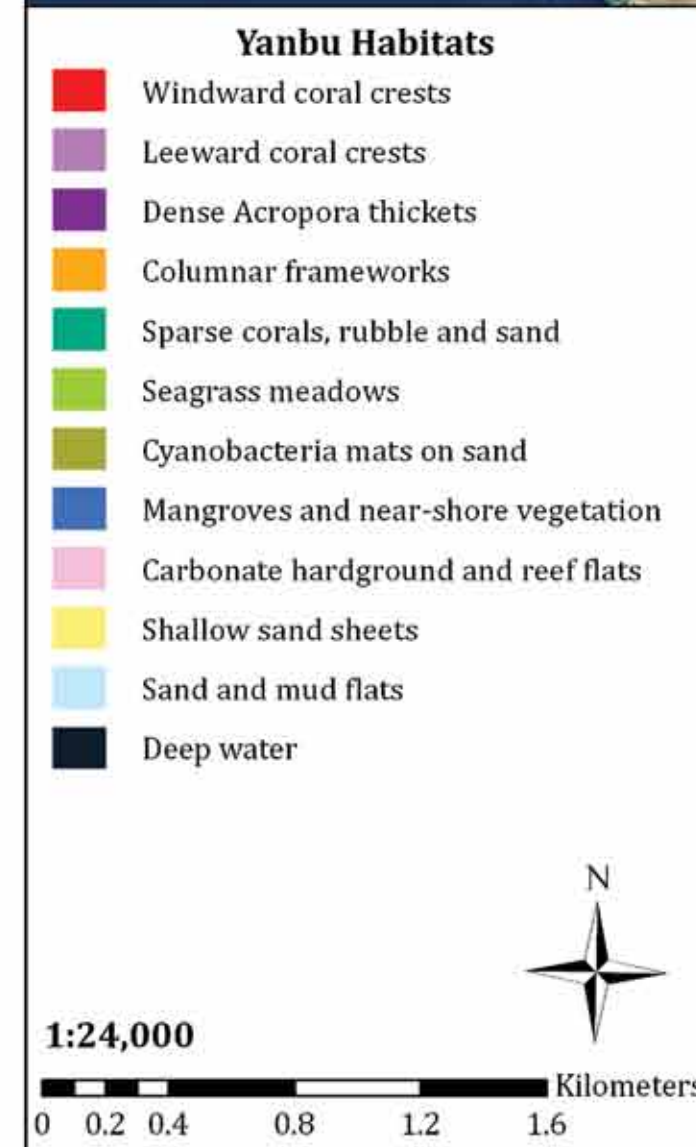
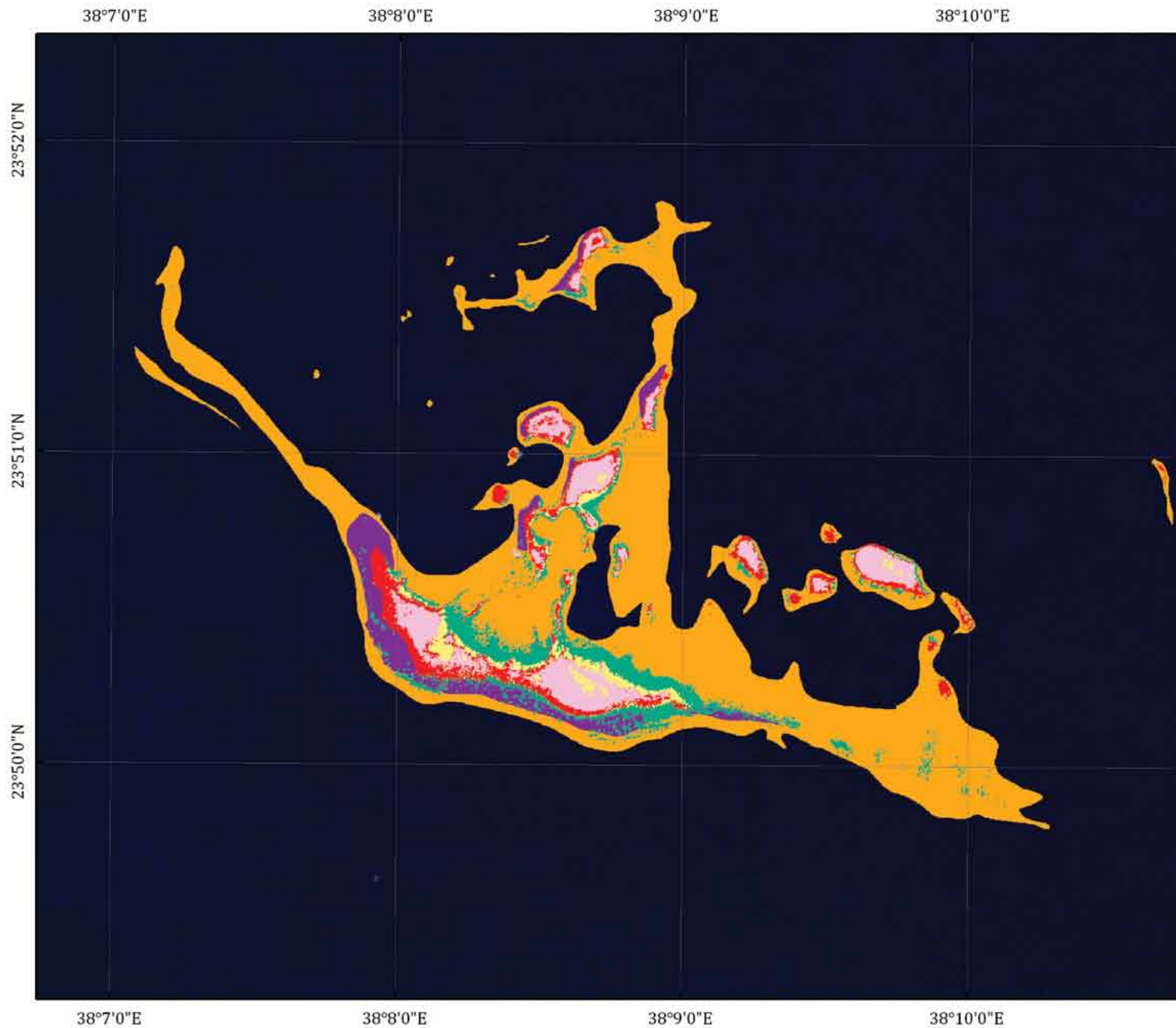
**Yanbu Habitats**

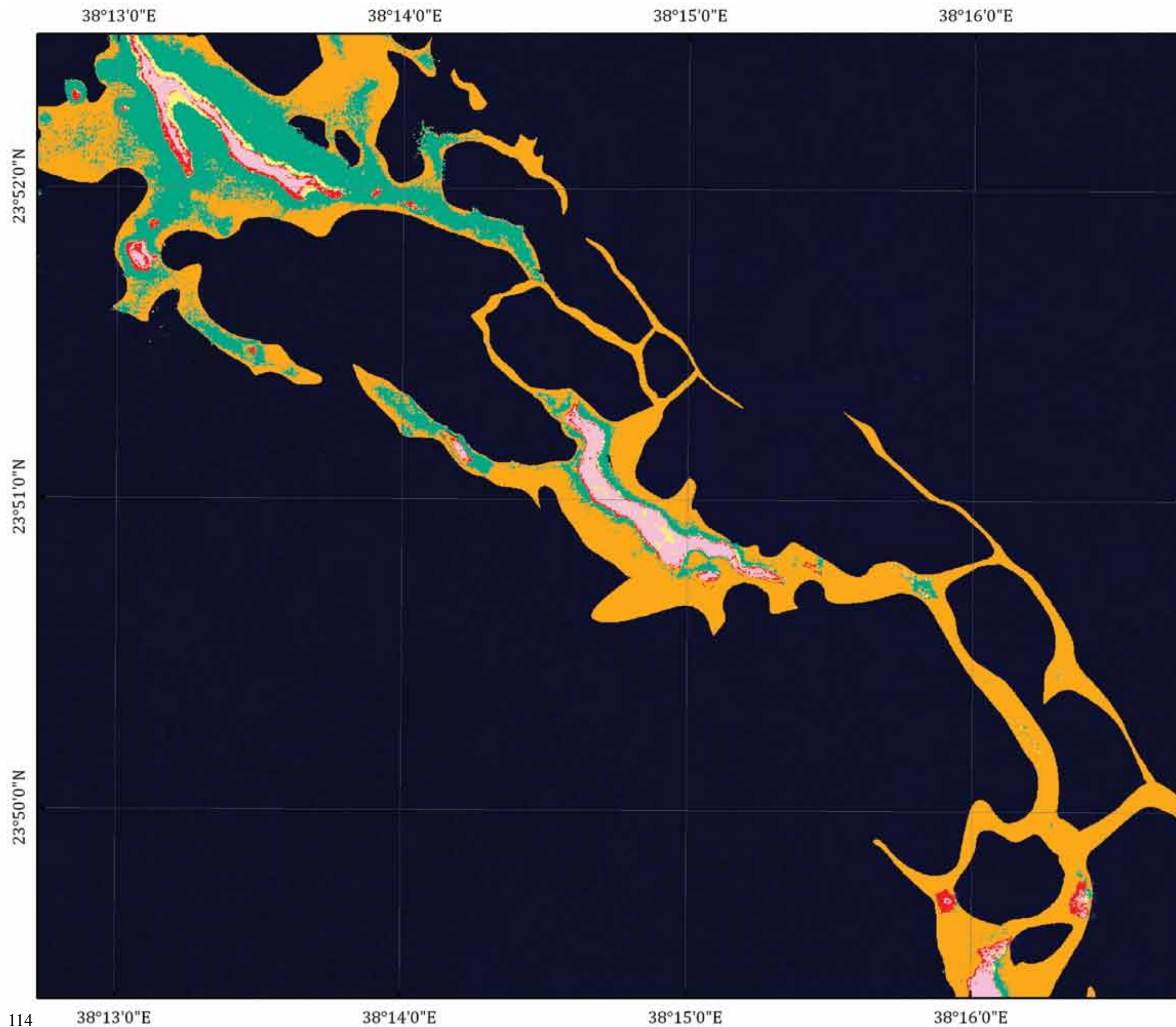
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- Shallow sand sheets
- Sand and mud flats
- Deep water

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 1:24,000  
  
 Kilometers









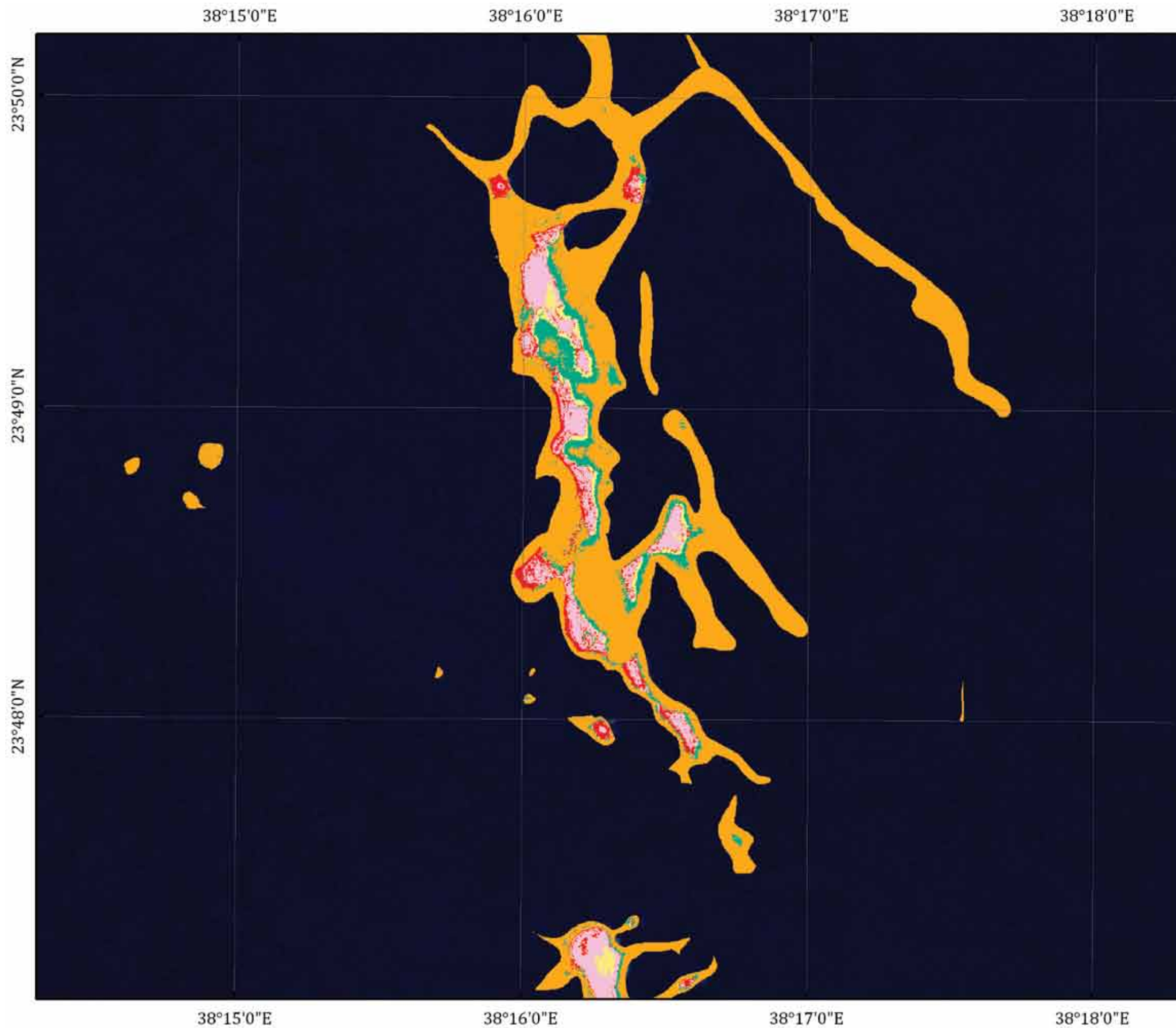
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**1:24,000**





**Yanbu Habitats**

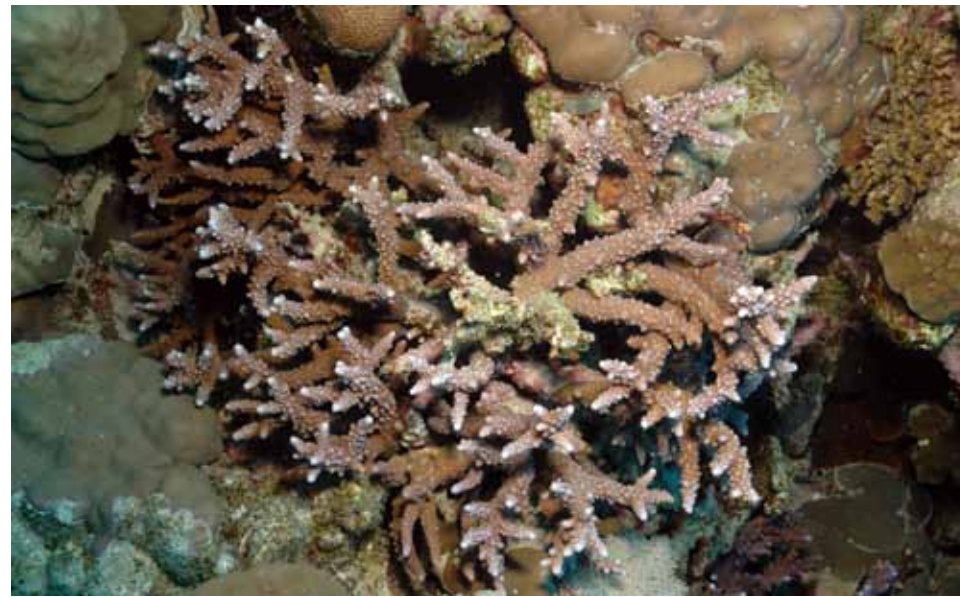
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**1:24,000**

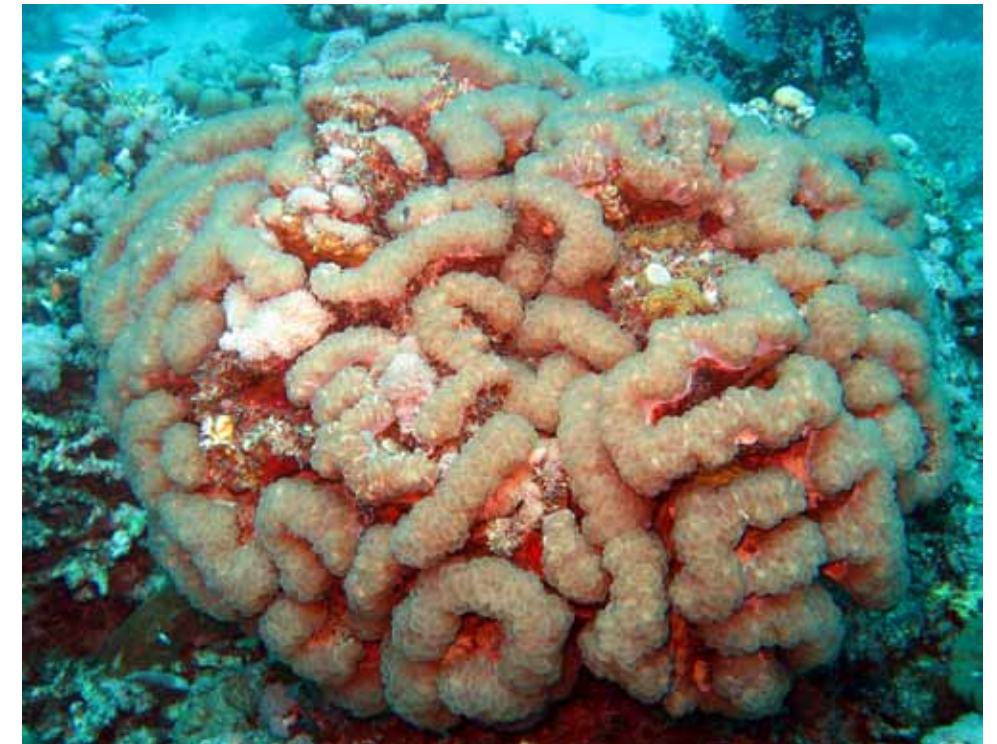




Dense stands of *Pocillopora* were found within the reef crest (2-4 m depth) on some offshore reefs.



The genus *Acropora* contains more species than any other genera and has multiple growth forms. Some species (*A. hemprichii*, top center) produce long branches in a protected environment and compact thickets with short branches in shallow water exposed to wave action (middle center).



Isolated colonies of bubble coral (*Plerogyra sinuosa*) were found on most reefs in the Yanbu region. The bubbles are water-filled vesicles that are thought to regulate the amount of light the coral receives. Sweeper tentacles are extended at night; these have a powerful sting and are used to capture food.



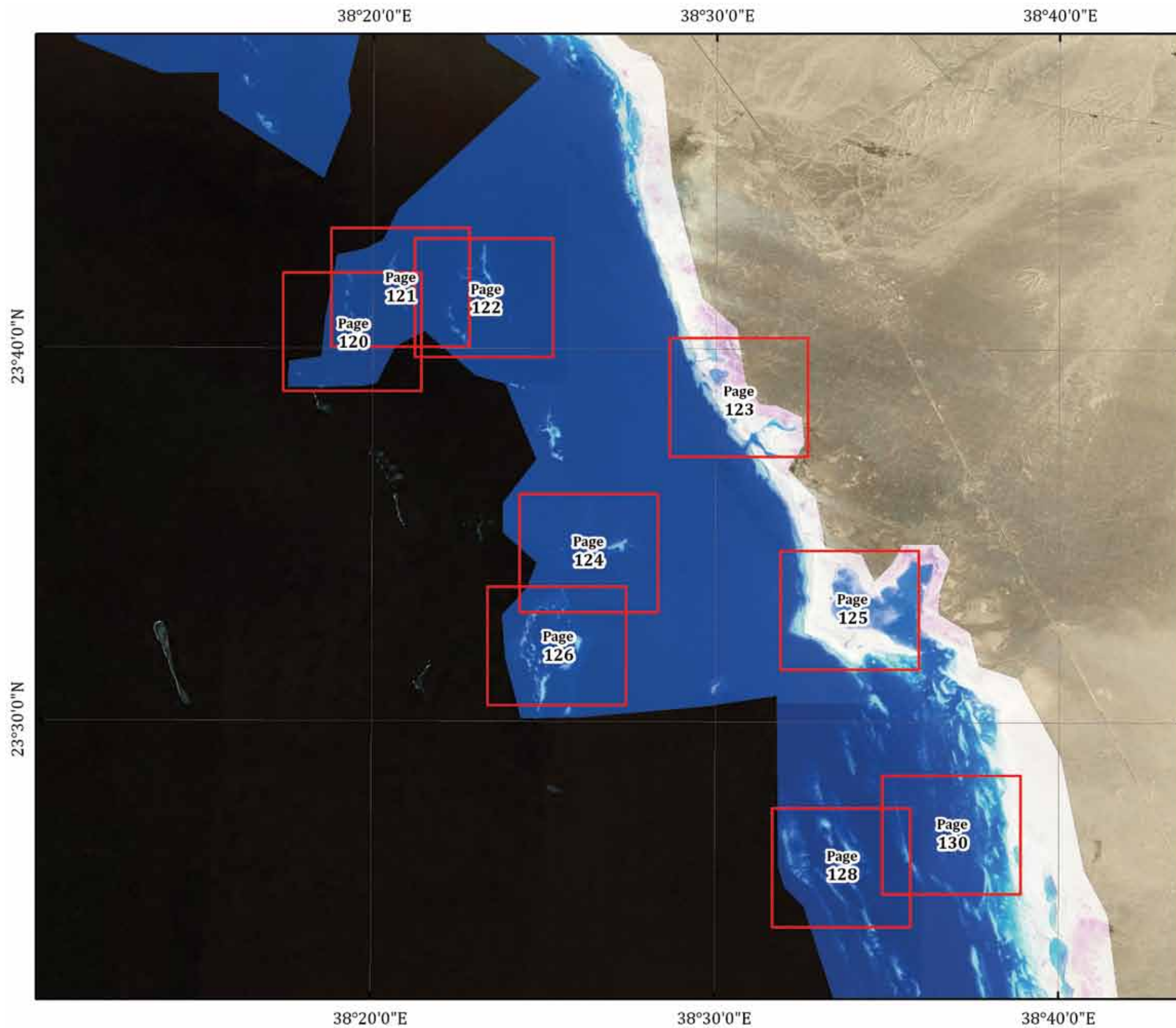
Small colonies of *Turbinaria* encrusted the bottom at mid-depths (3-10 m) and formed larger overlapping plates on walls.



Right: Leather coral (*Sarcophyton*) is a soft coral without a skeleton that commonly colonizes dead coral skeletons and can form large aggregations.



The genus *Pocillopora* was extremely common on Yanbu's reefs. While small colonies were usually completely live, larger colonies were targeted by coral-eating snails that consumed the colony in a linear manner.



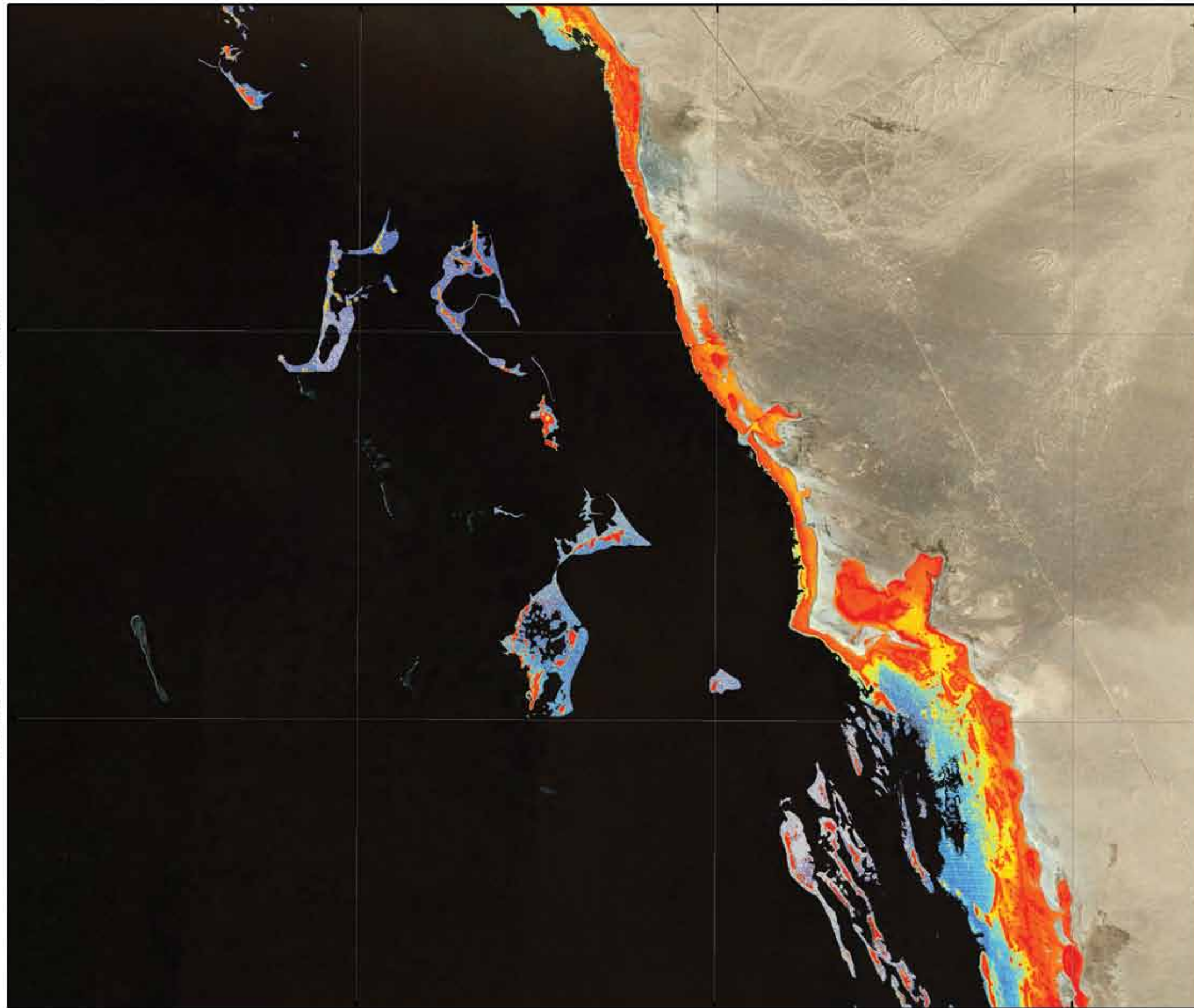
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38°30'0"E

38°40'0"E

23°40'0"N

23°30'0"N

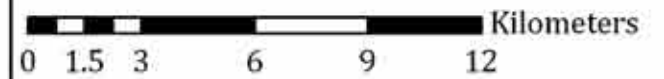


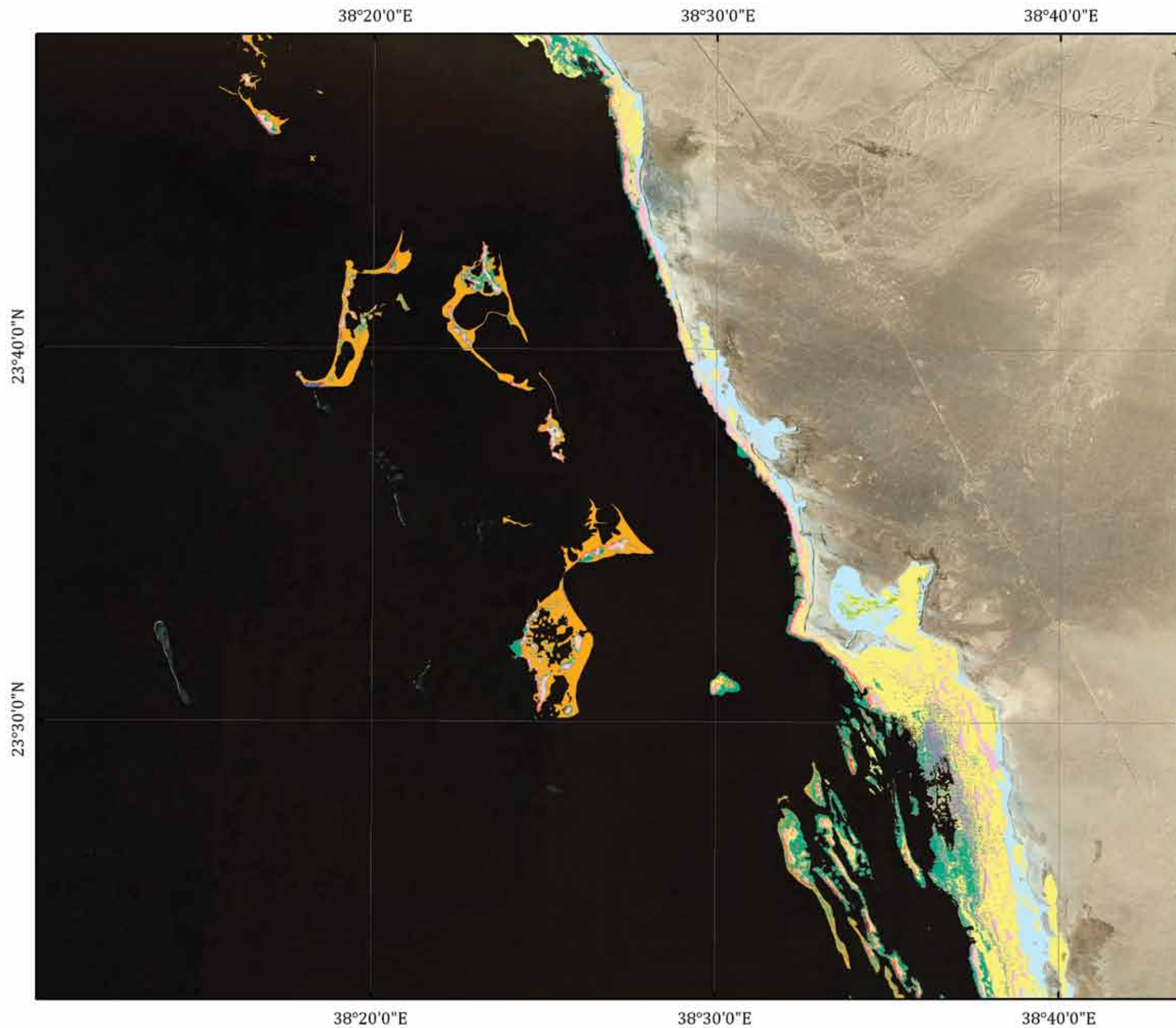
**Yanbu Bathymetry**

Depth, meters

0 - 0.9	14 - 14.9
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3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

**1:200,000**





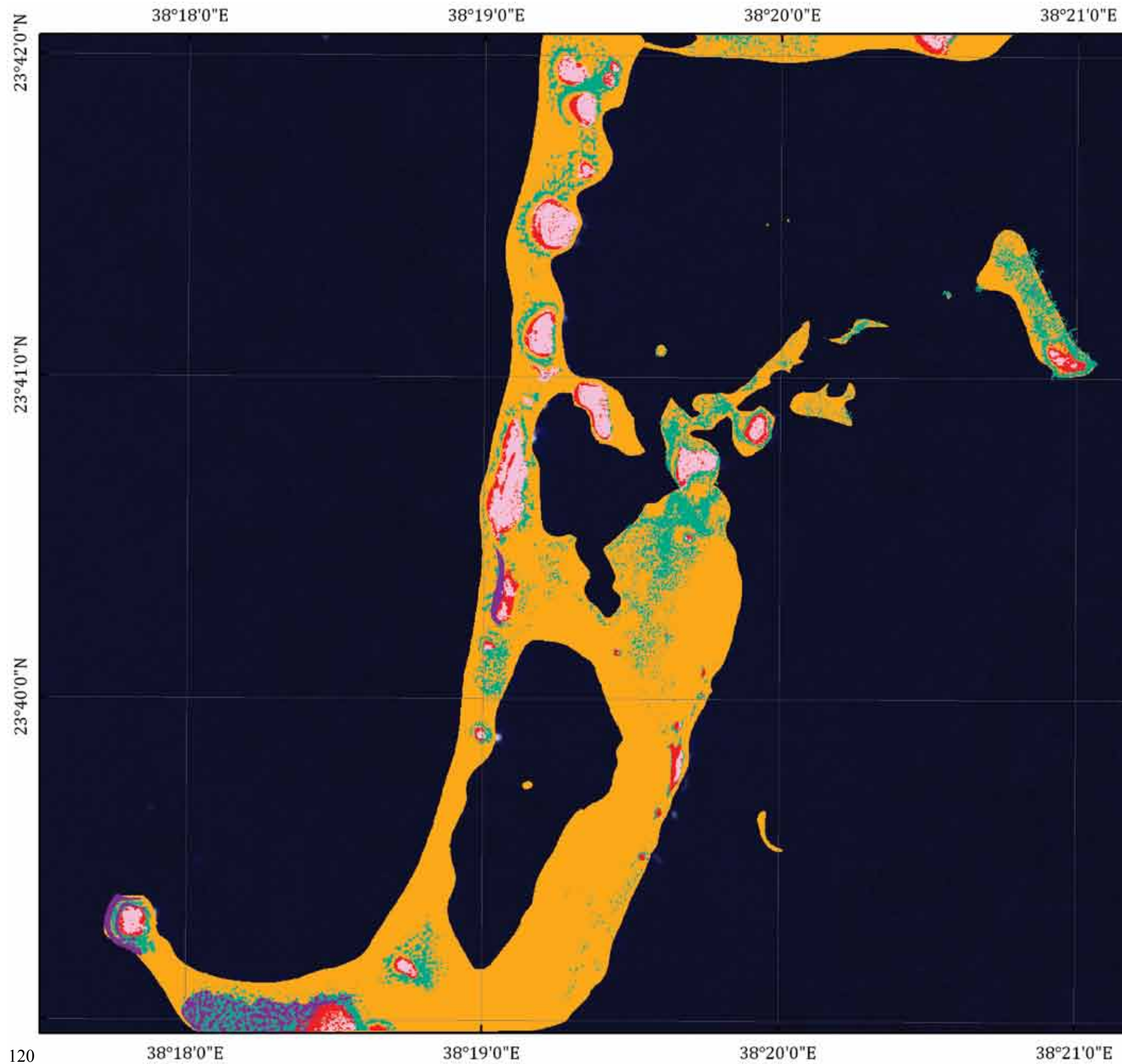
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1:200,000







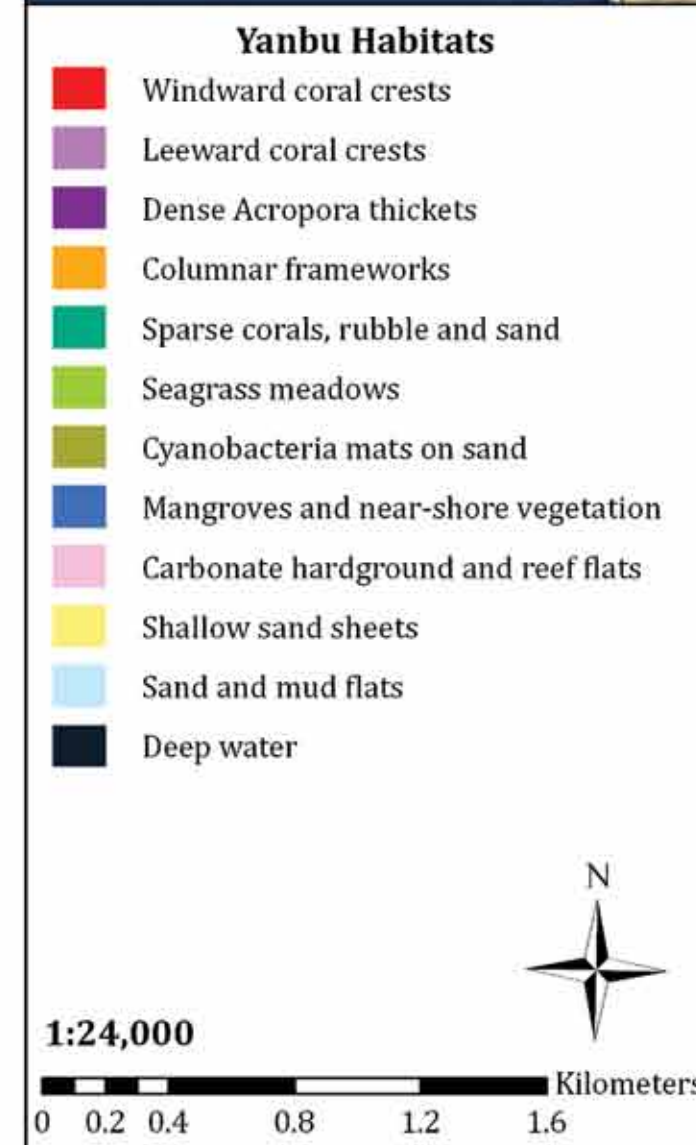
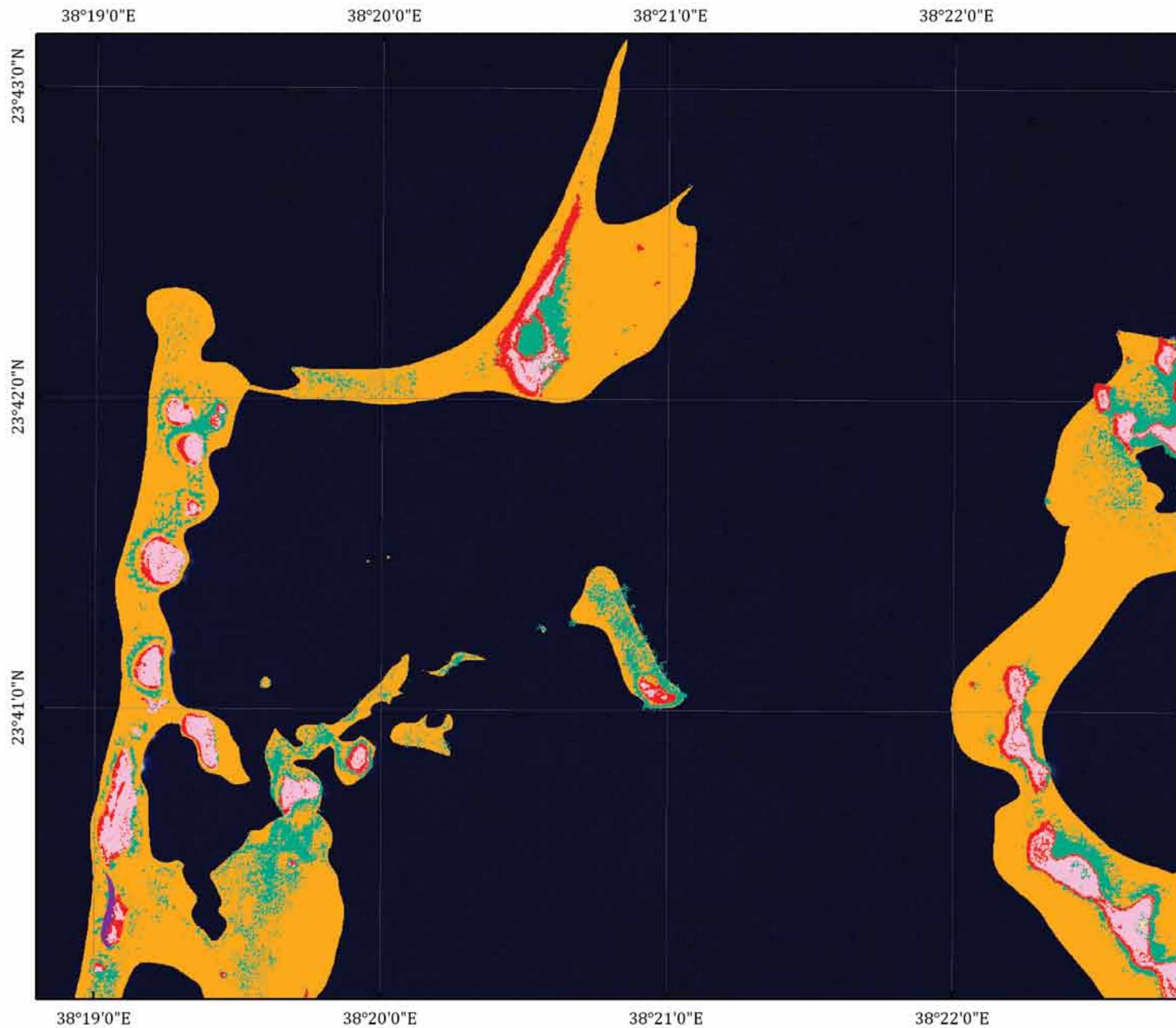
**Yanbu Habitats**

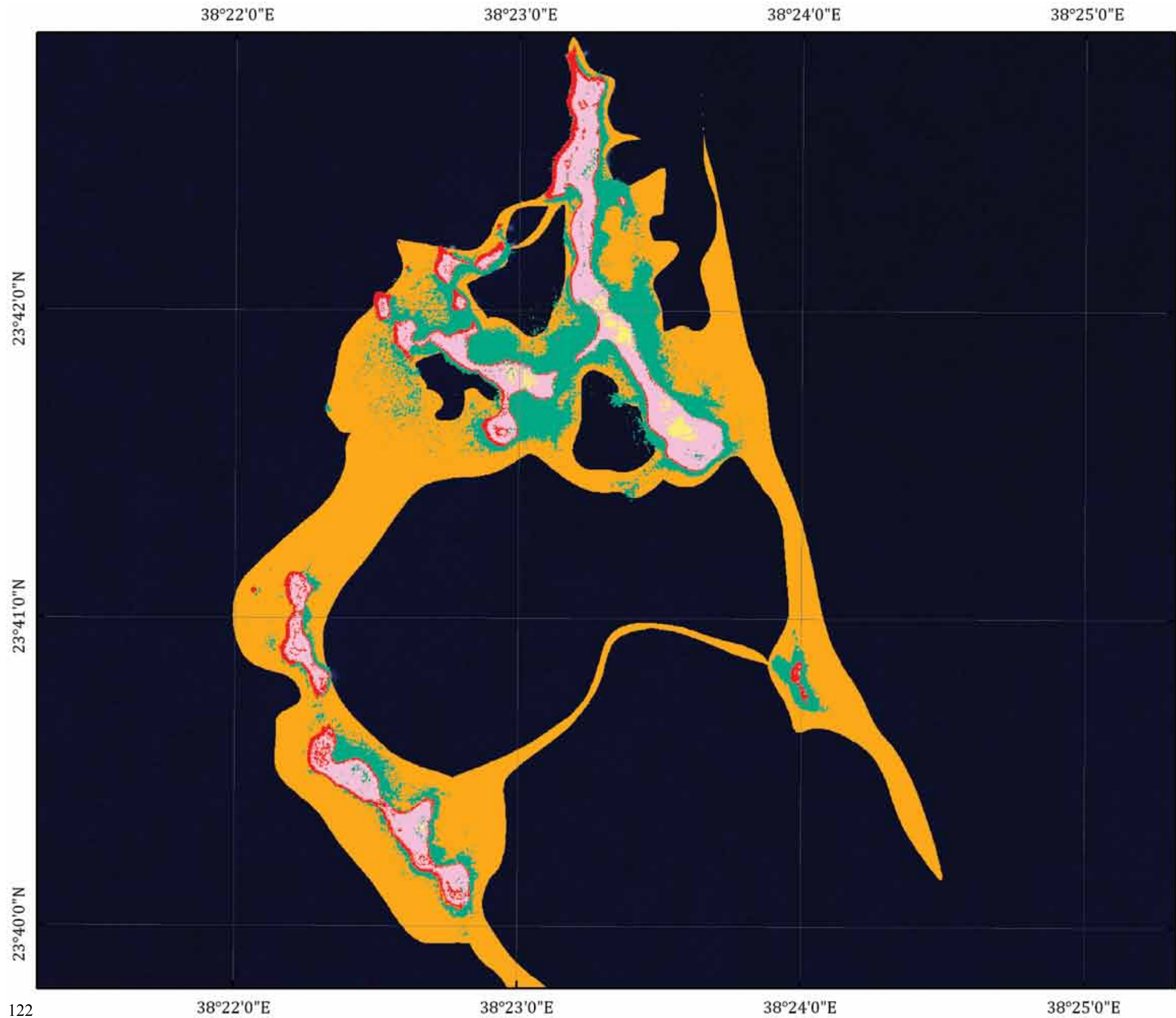
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**1:24,000**

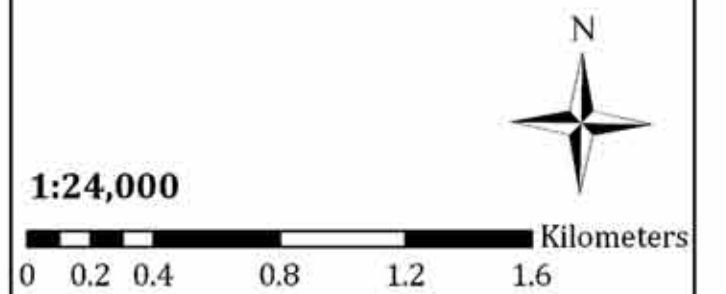


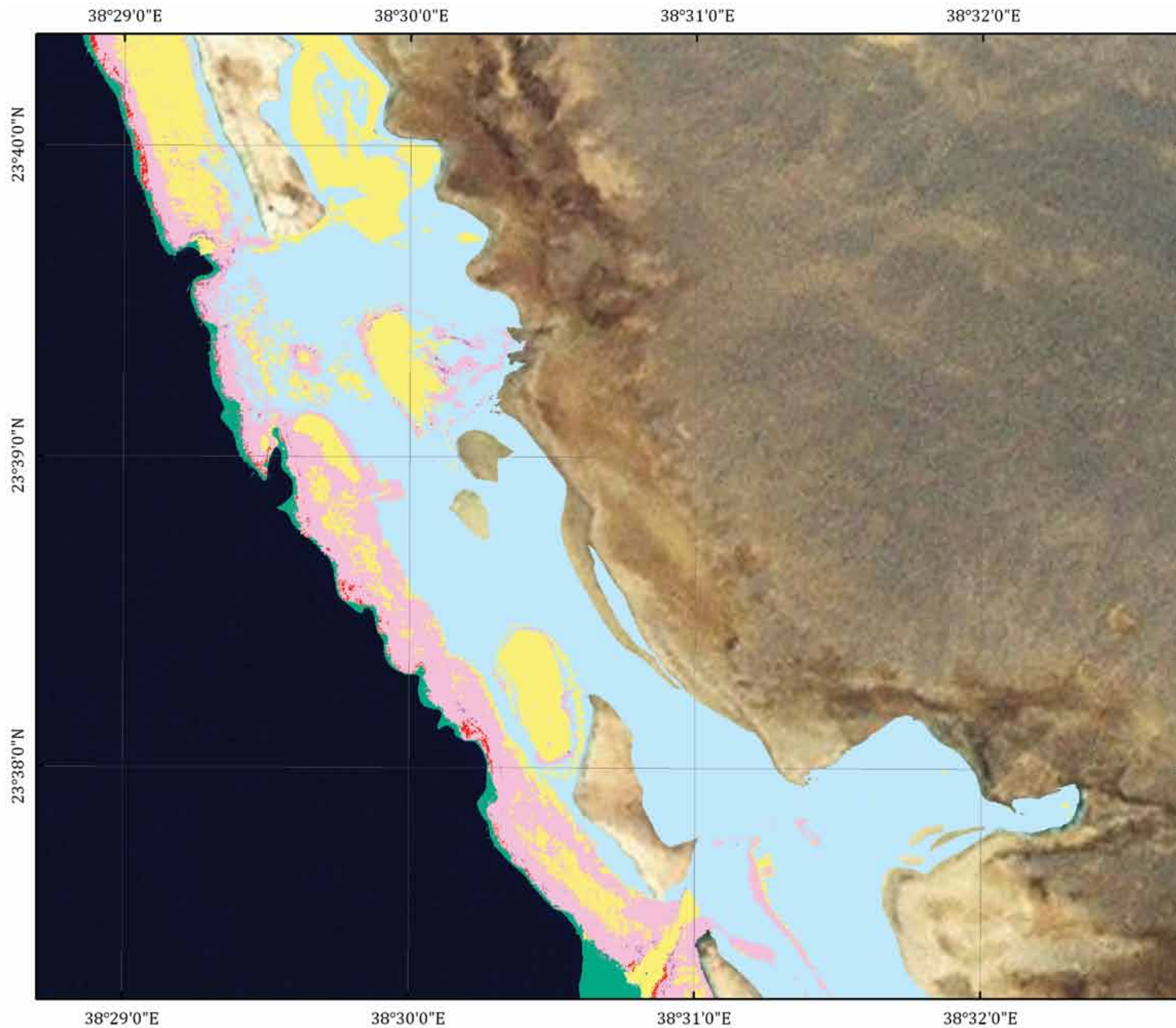




### Yanbu Habitats

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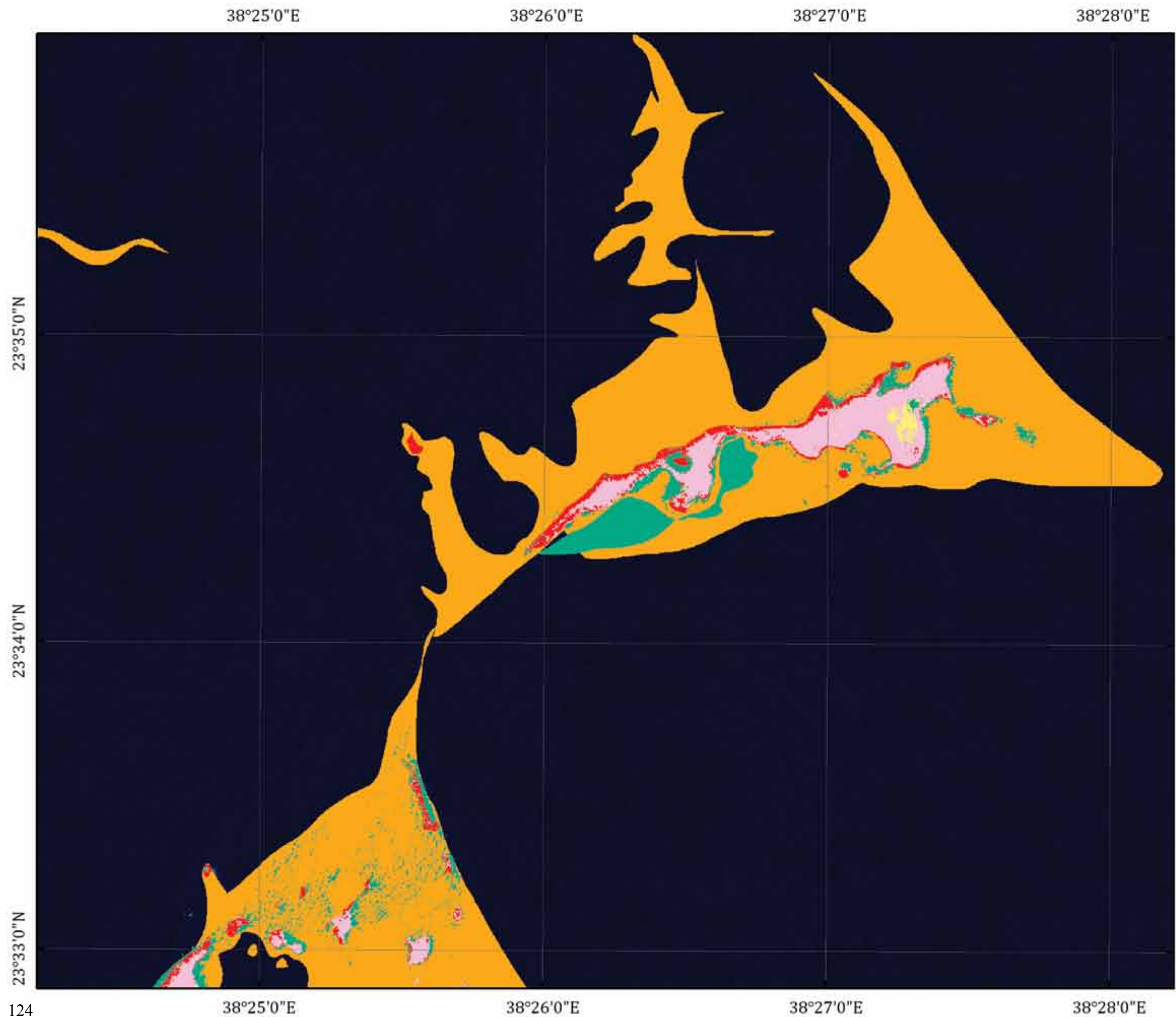


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- Sand and mud flats
- Deep water

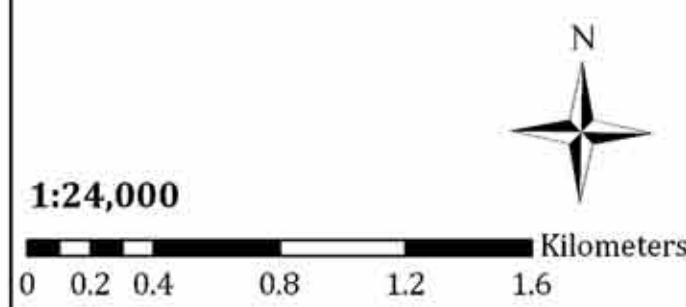
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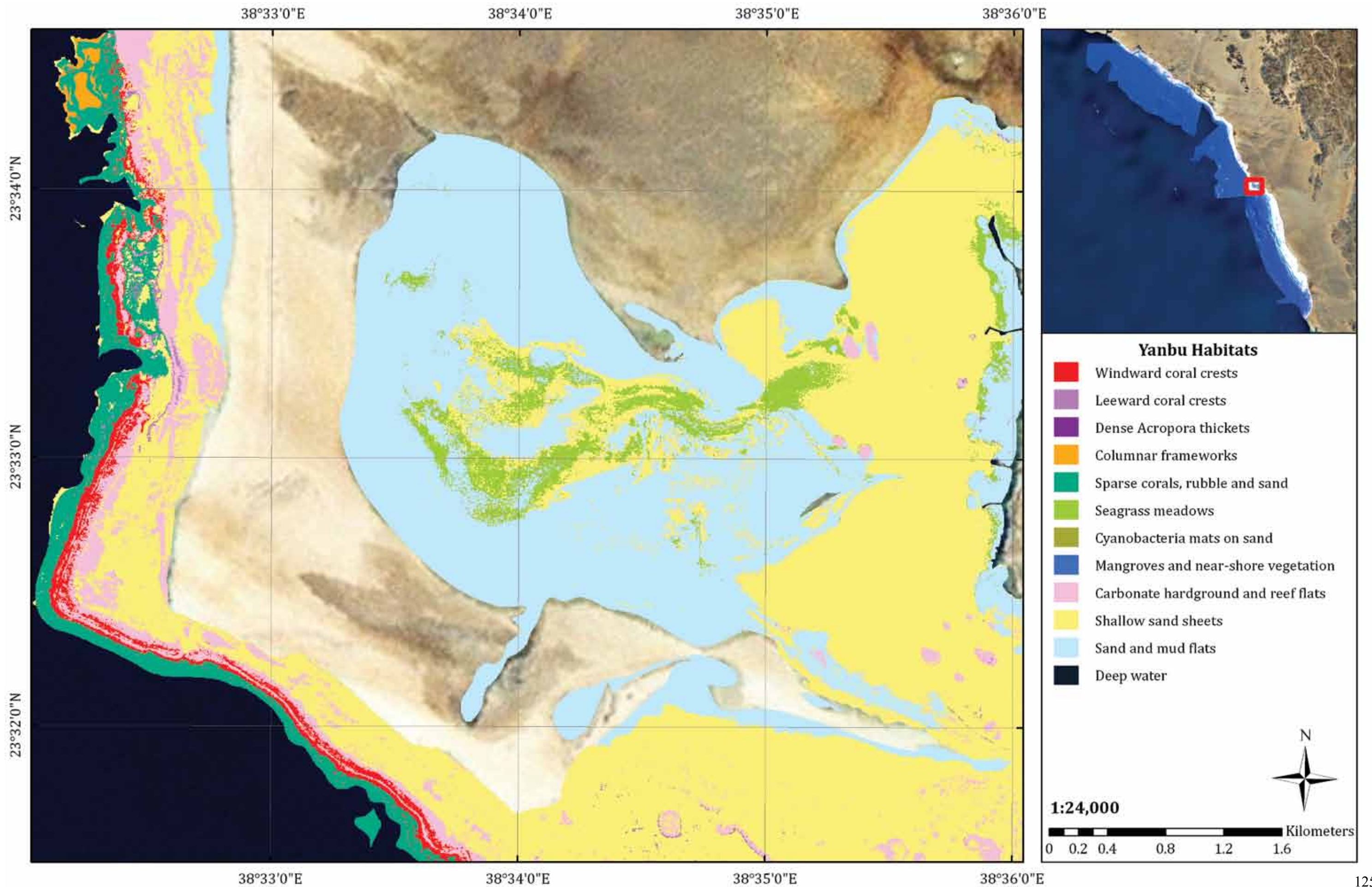


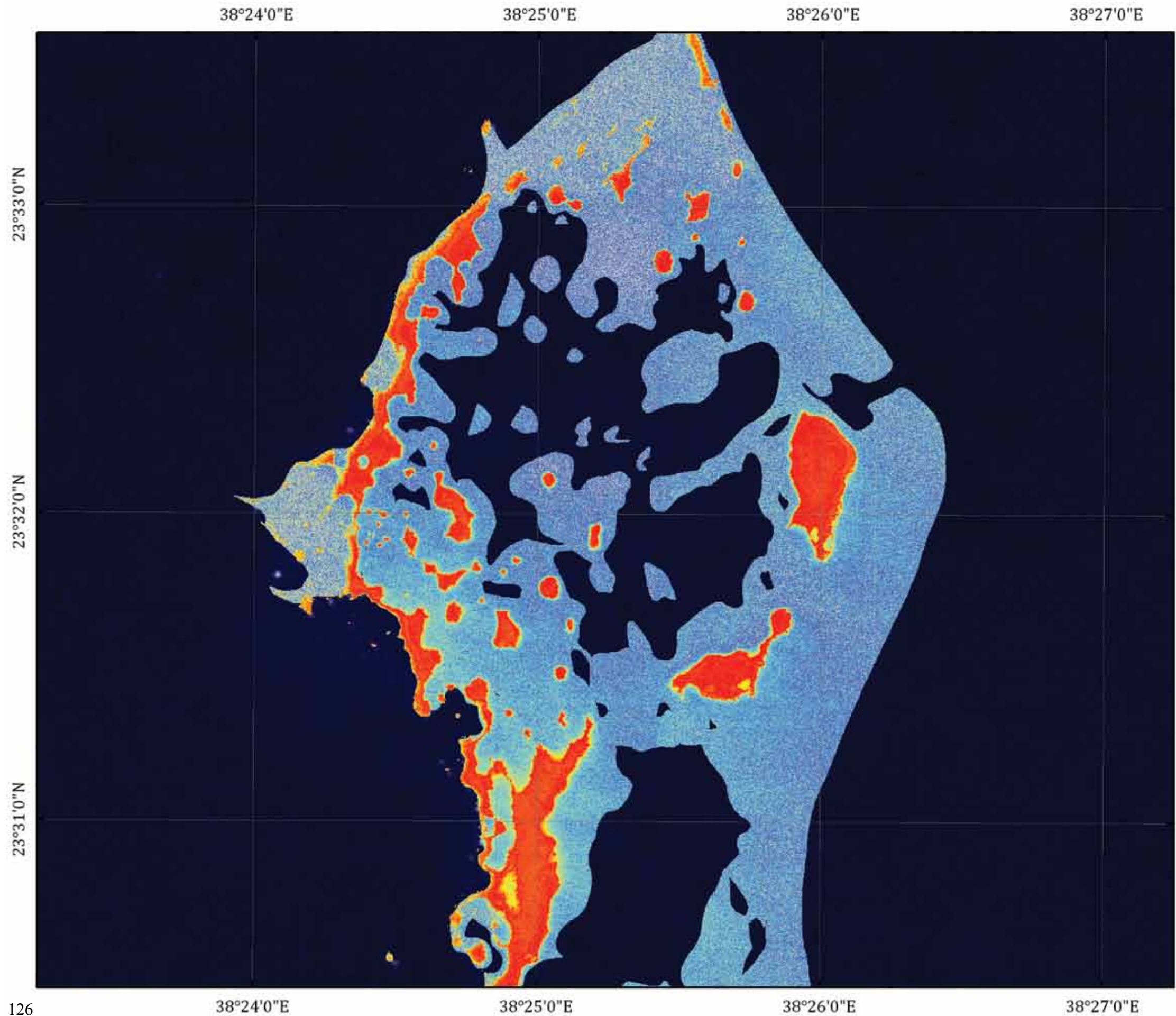


**Yanbu Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
- Seagrass meadows
- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water







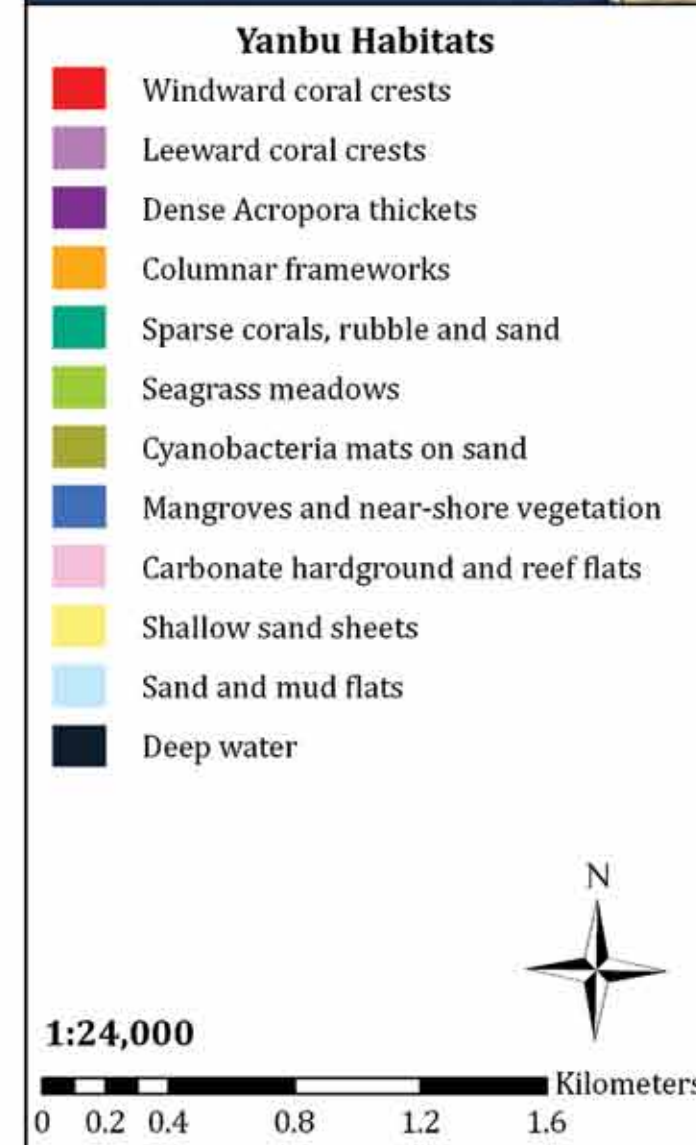
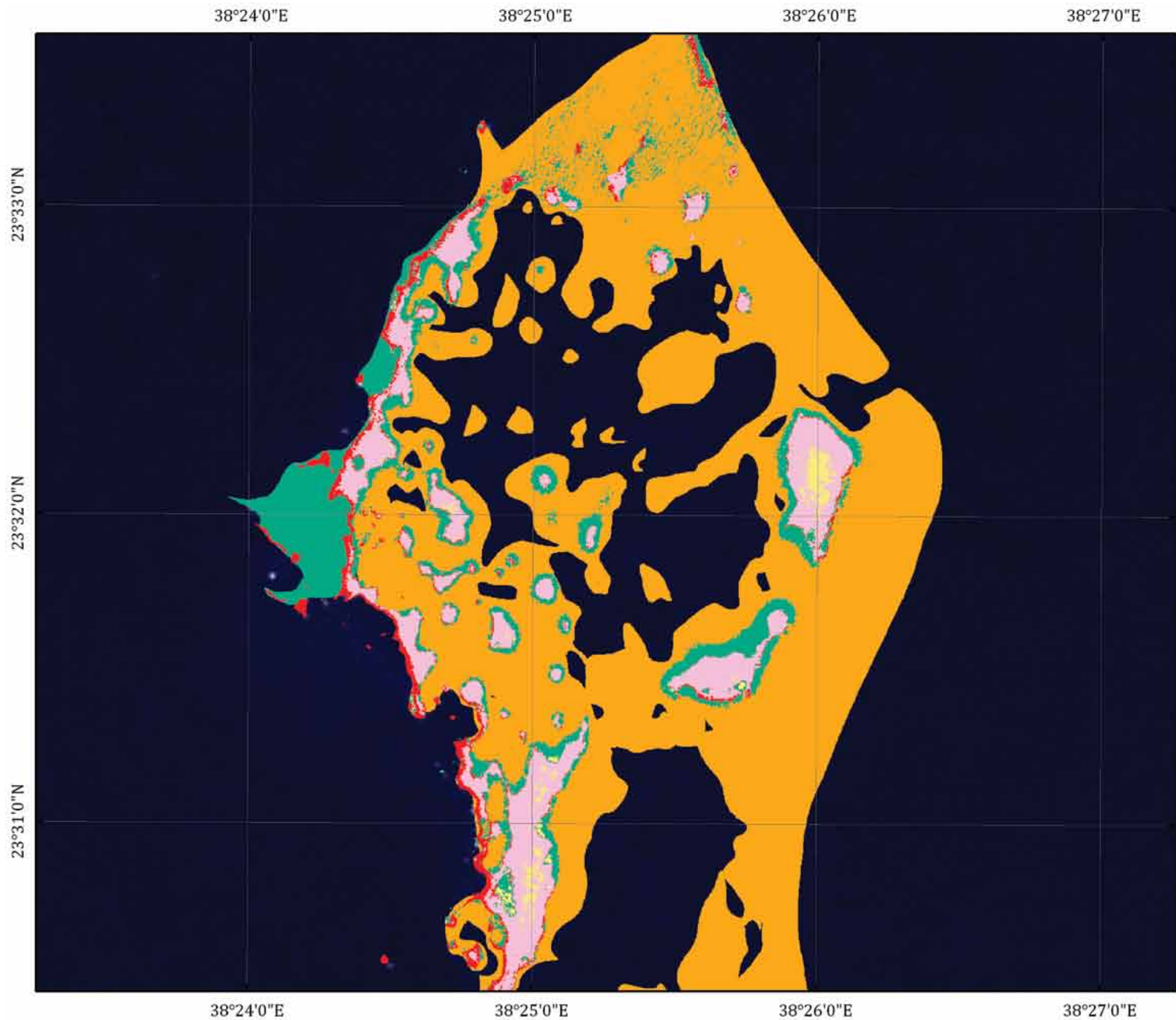
### Yanbu Bathymetry

Depth, meters

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

1:24,000







38°32'0"E

38°33'0"E

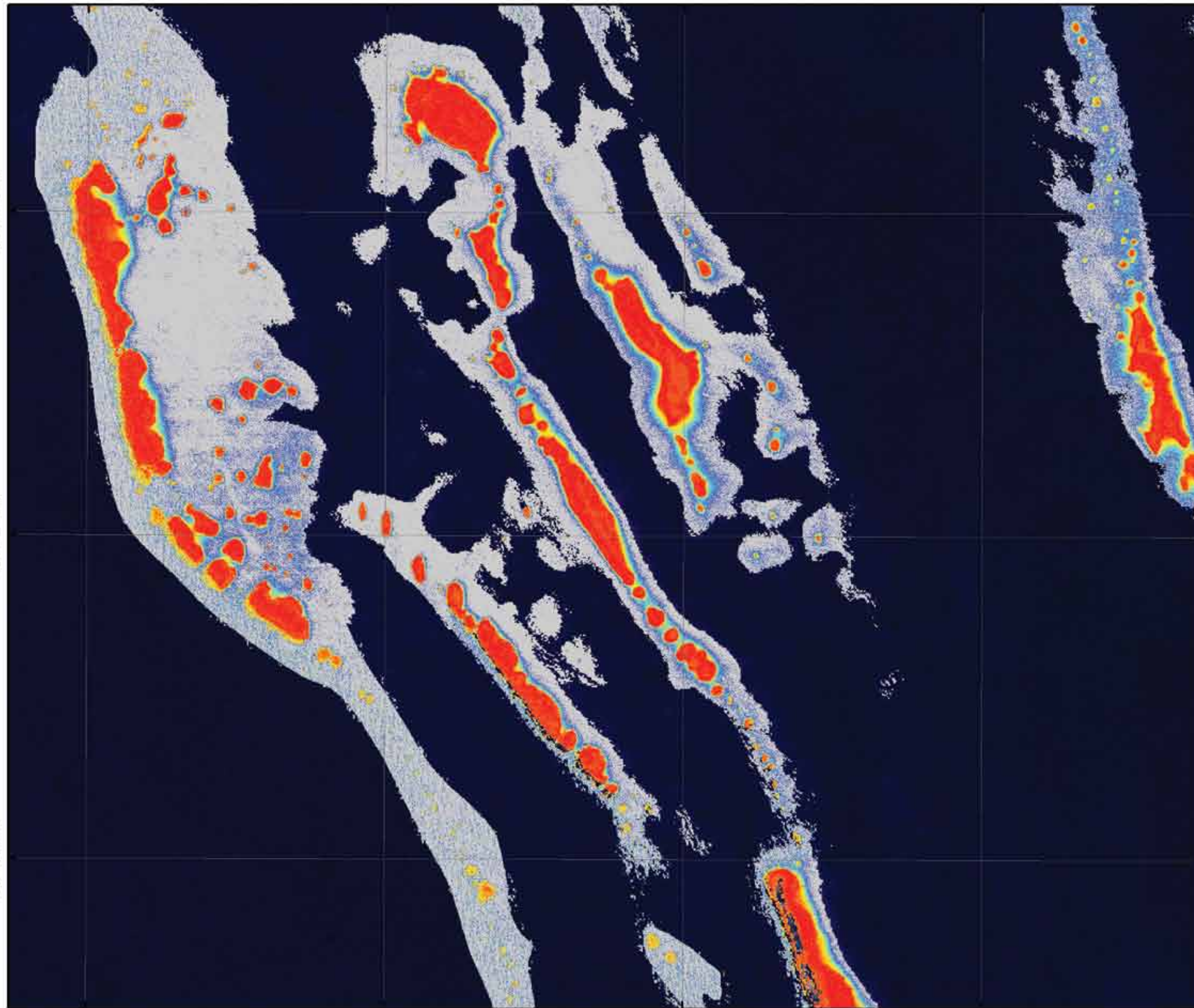
38°34'0"E

38°35'0"E

23°27'0"N

23°26'0"N

23°25'0"N



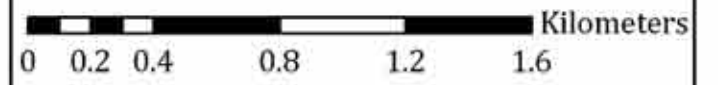
### Yanbu Bathymetry

Depth, meters

	0 - 0.9		14 - 14.9
	1 - 1.9		15 - 15.9
	2 - 2.9		16 - 16.9
	3 - 3.9		17 - 17.9
	4 - 4.9		18 - 18.9
	5 - 5.9		19 - 19.9
	6 - 6.9		20 - 20.9
	7 - 7.9		21 - 21.9
	8 - 8.9		22 - 22.9
	9 - 9.9		23 - 23.9
	10 - 10.9		24 - 24.9
	11 - 11.9		25 - 40
	12 - 12.9		Deep water
	13 - 13.9		



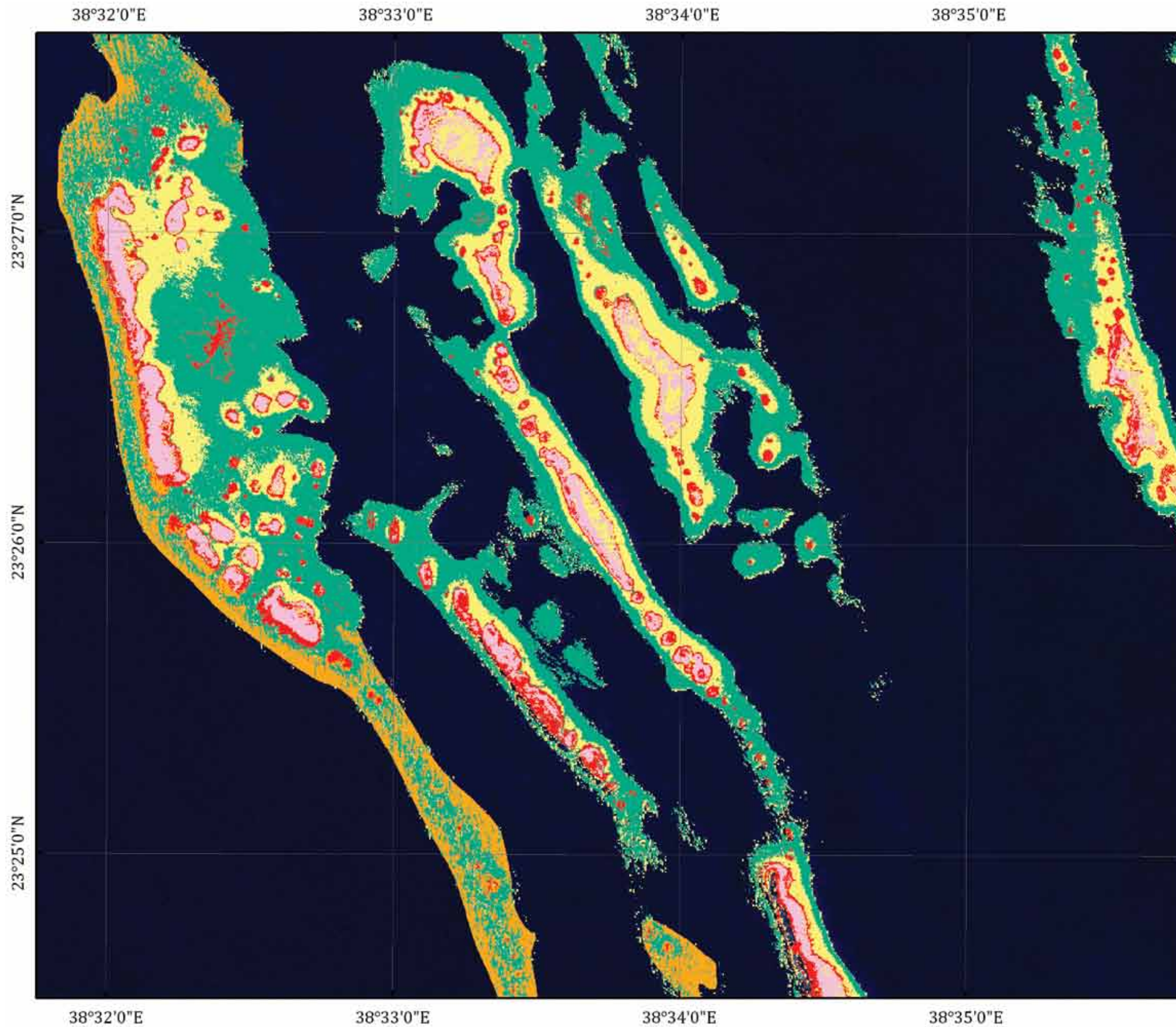
1:24,000



38°33'0"E

38°34'0"E

38°35'0"E



**Yanbu Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
- Seagrass meadows
- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water



1:24,000



38°32'0"E

38°33'0"E

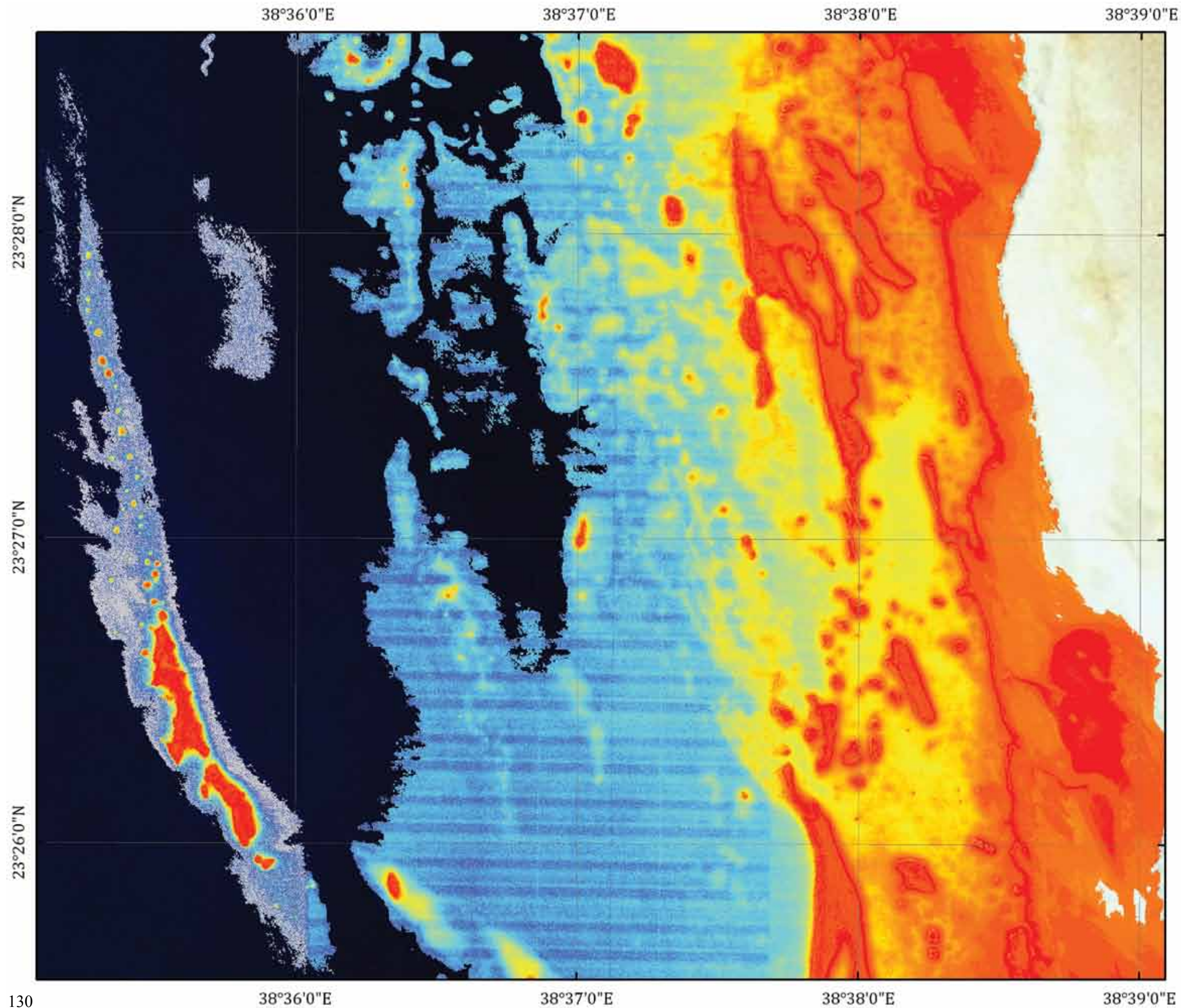
38°34'0"E

38°35'0"E

23°27'0"N

23°26'0"N

23°25'0"N



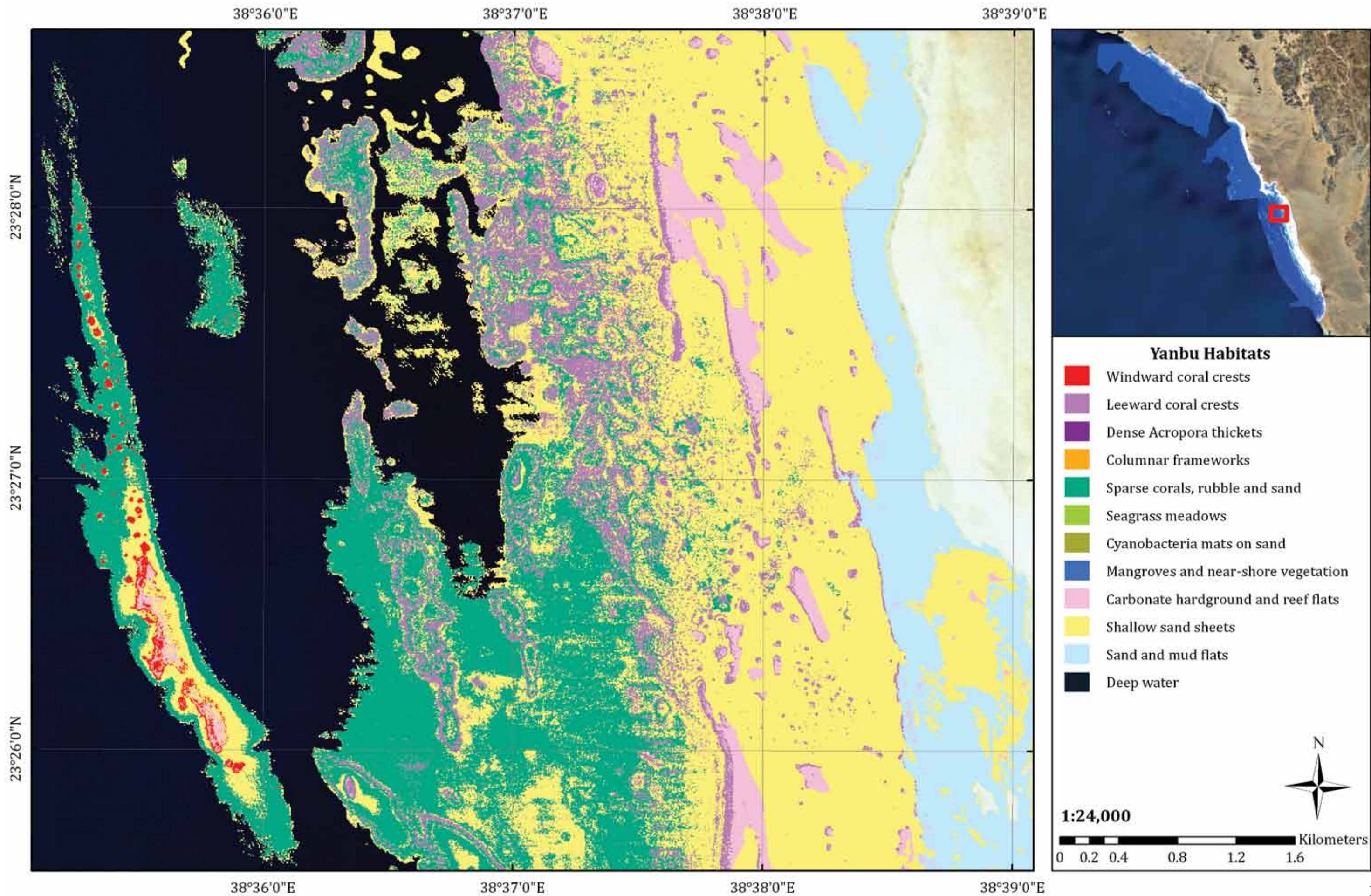
**Yanbu Bathymetry**

**Depth, meters**

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

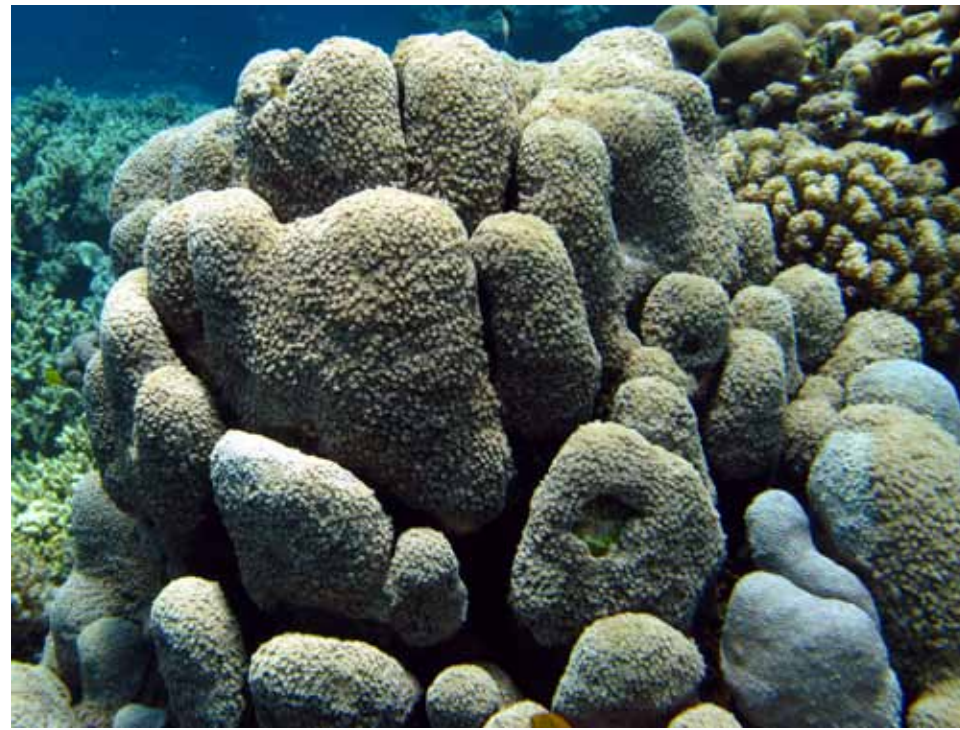
**1:24,000**







An elongate, slipper-shaped free-living fungiid coral (*Ctenactis echinata*) below a massive faviid coral (*Favia stelligera*).



Massive corals in the genus *Goniopora* extend their tentacles during the daylight. These corals are closely related to the dominant framebuilder, *Porites*. They tend to occur in turbid, lagoonal environments and can form unusually large colonies.



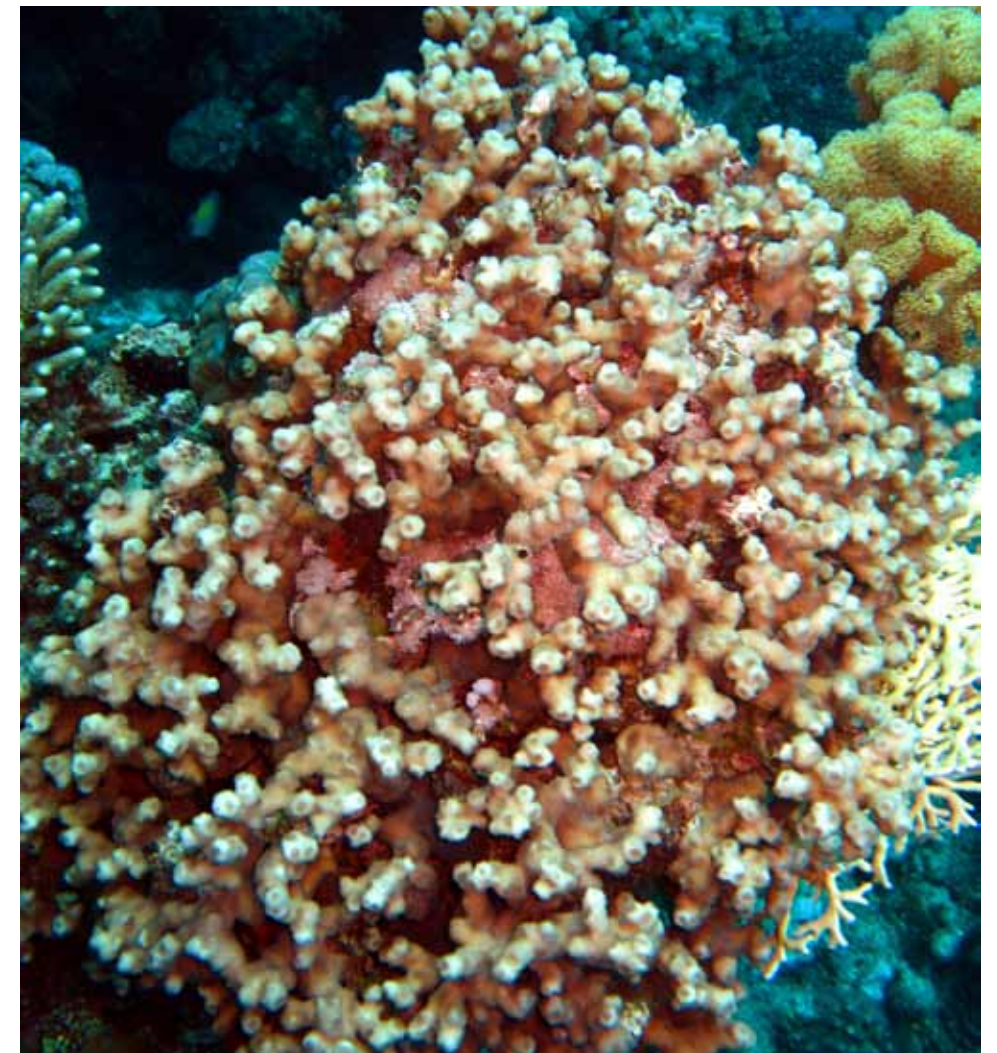
A large columnar lobate colony of *Porites lutea* in shallow water.



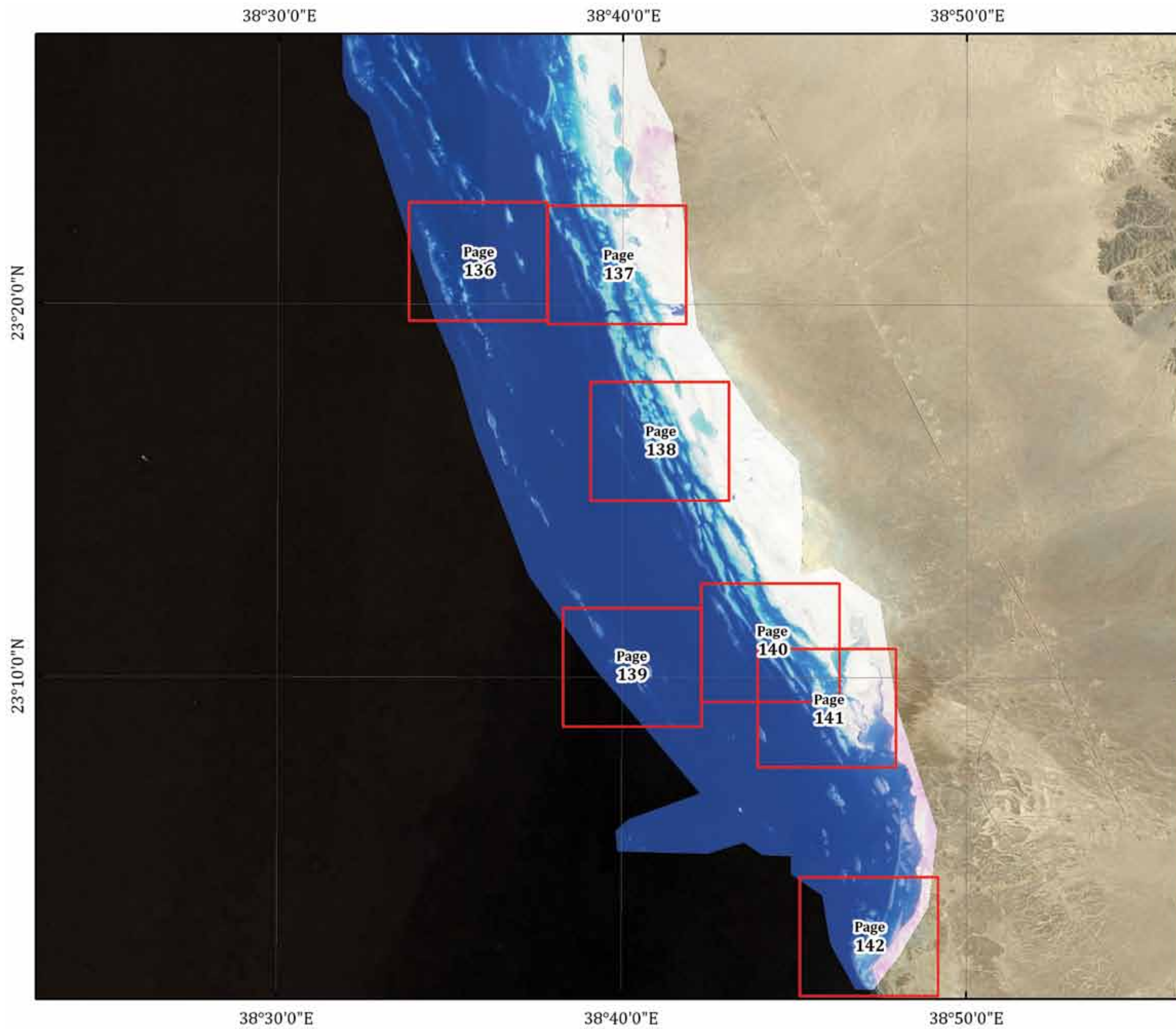
Colonies of the hydrozoan coral, *Millepora*, are found in the reef crest.

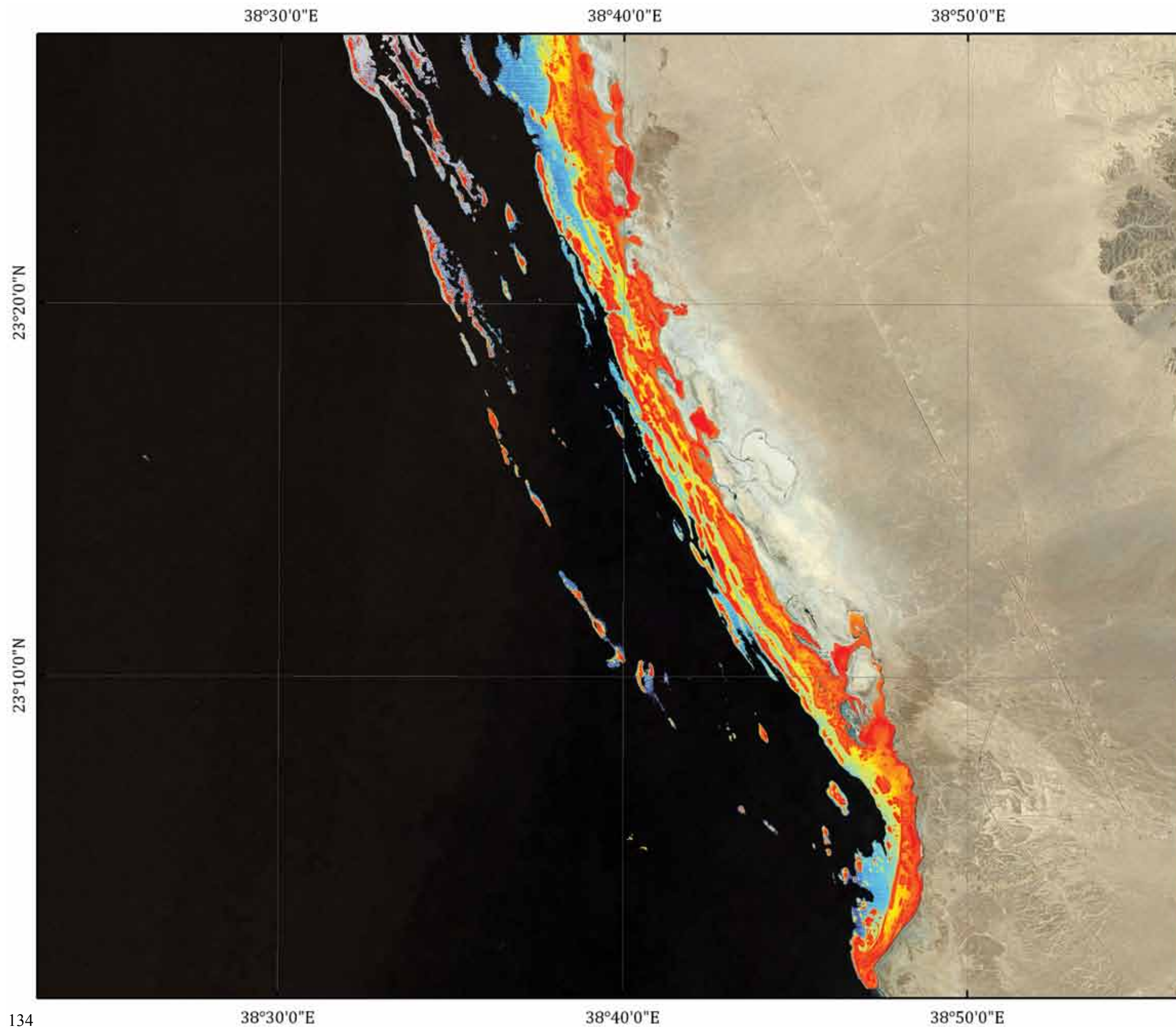


*Acropora cytherea* forms wide, flat tables that are relatively thin and finely branched. Branchlets often are upward projecting. On Yanbu's reefs, they are most common on outer reefs, occurring on the reef slope and also in sandy lagoons.



*Echinopora fruticulosa* forms dome-shaped clumps of interlocking branches. It is endemic to the Red Sea and parts of the Indian Ocean.



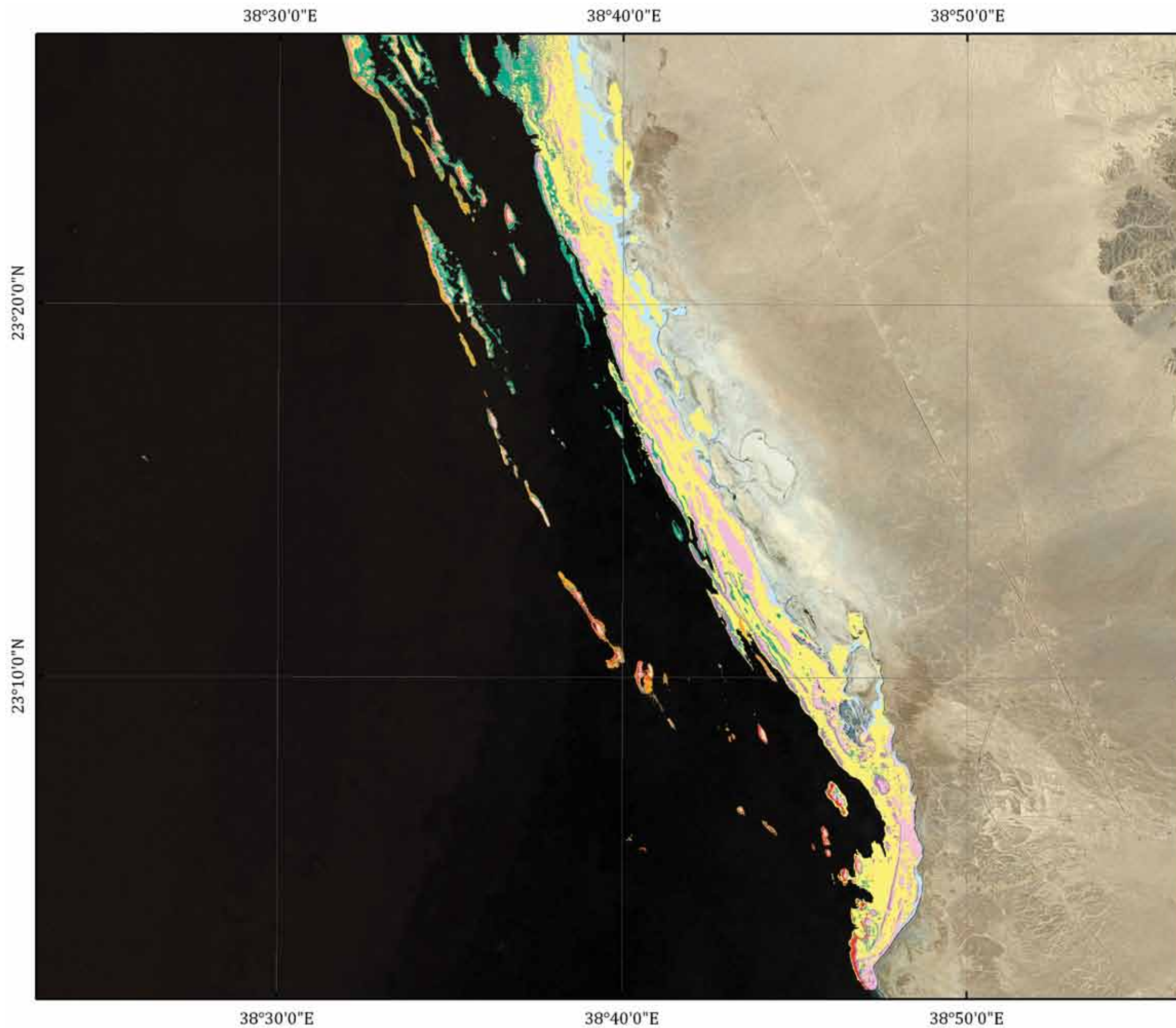


**Yanbu Bathymetry**

**Depth, meters**

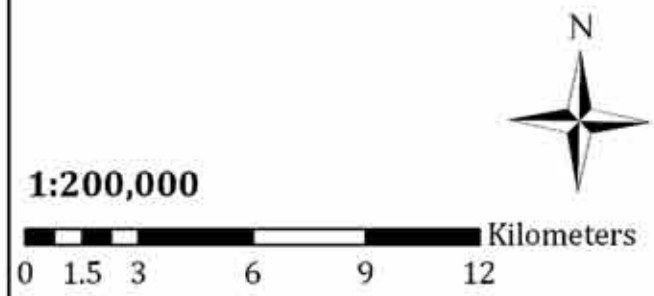
0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	





**Yanbu Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
- Seagrass meadows
- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water



38°30'0"E

38°40'0"E

38°50'0"E

23°20'0"N

23°10'0"N



38°34'0"E

38°35'0"E

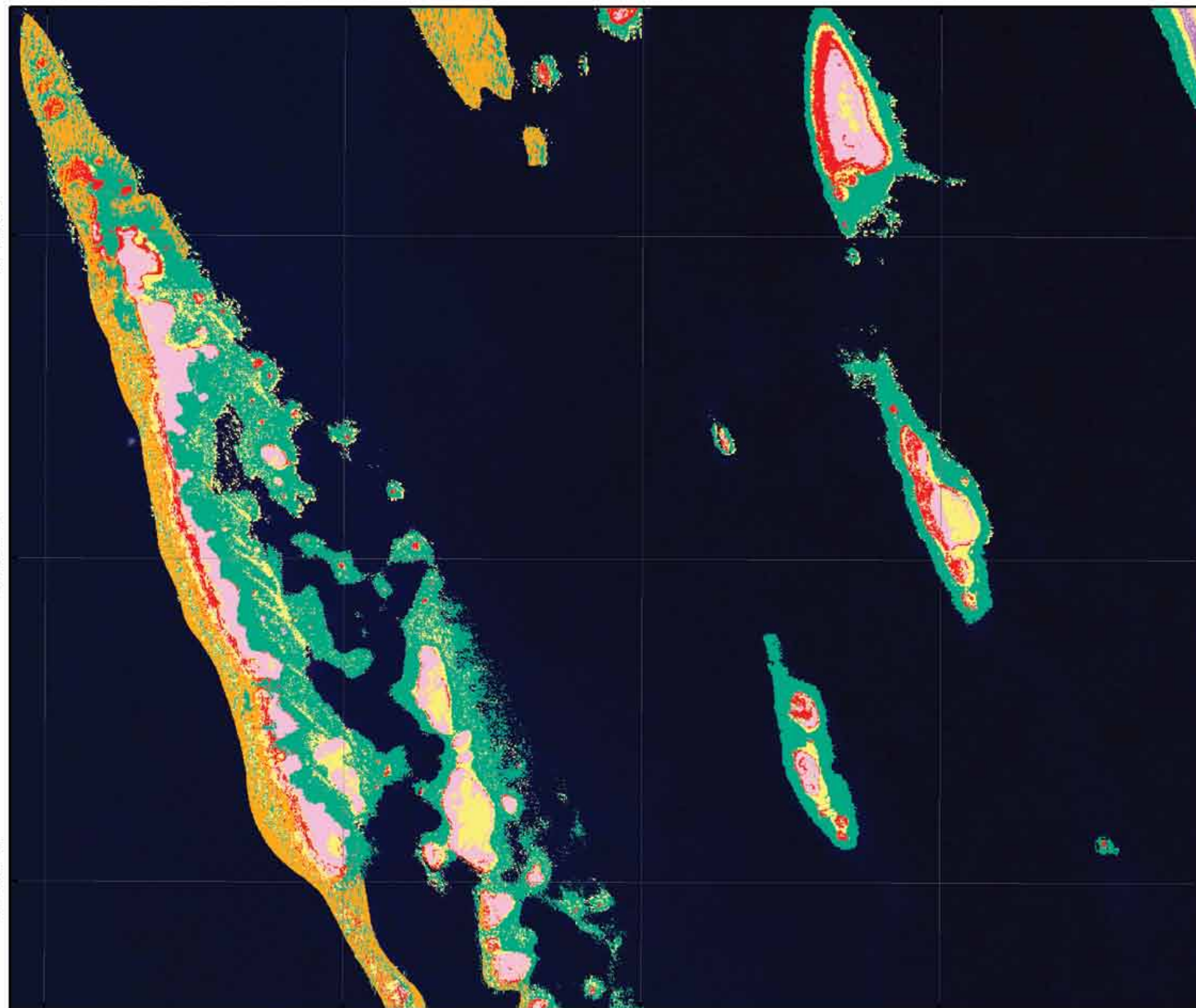
38°36'0"E

38°37'0"E

23°22'0"N

23°21'0"N

23°20'0"N



**Yanbu Habitats**

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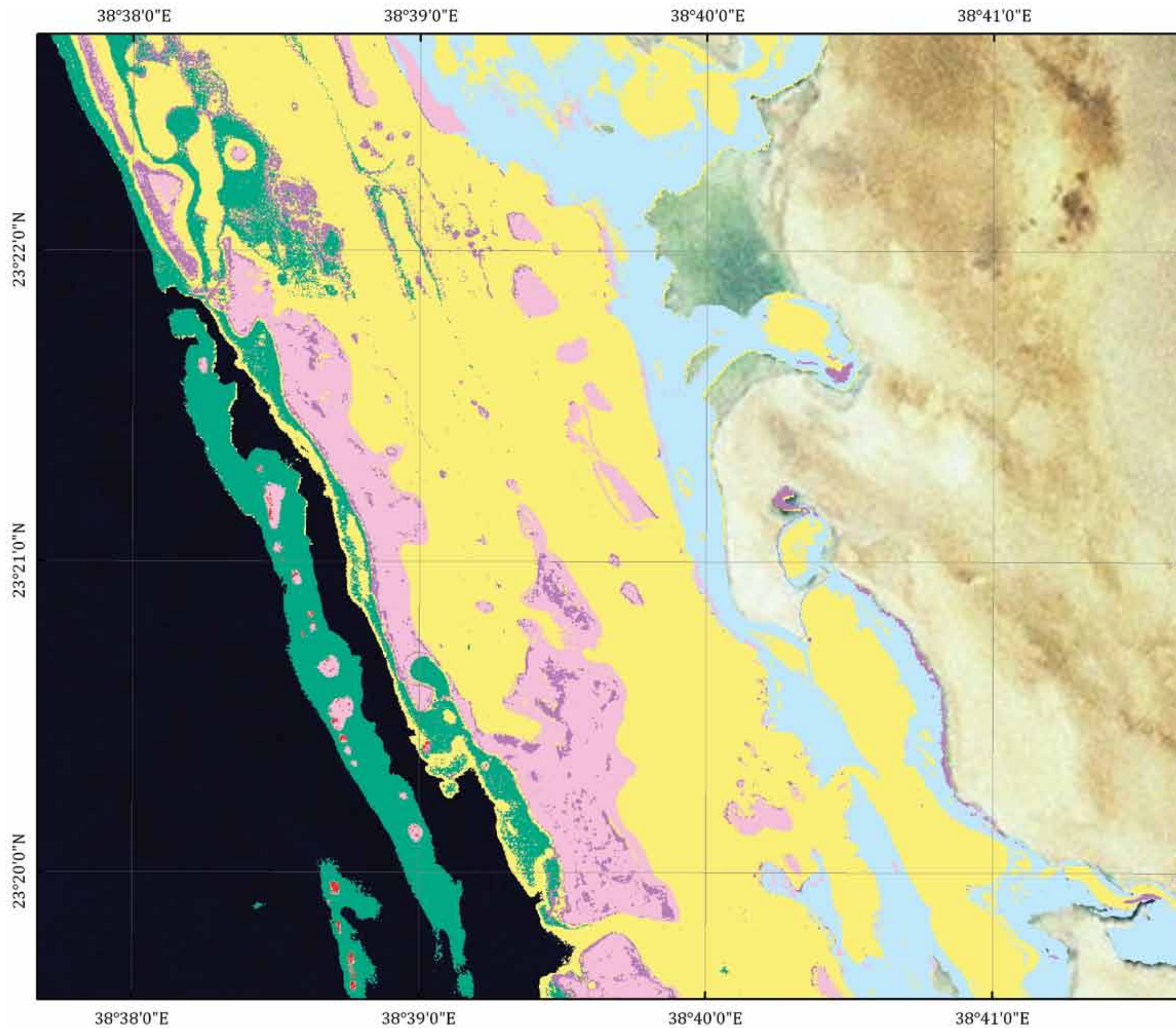
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38°35'0"E

38°36'0"E

38°37'0"E

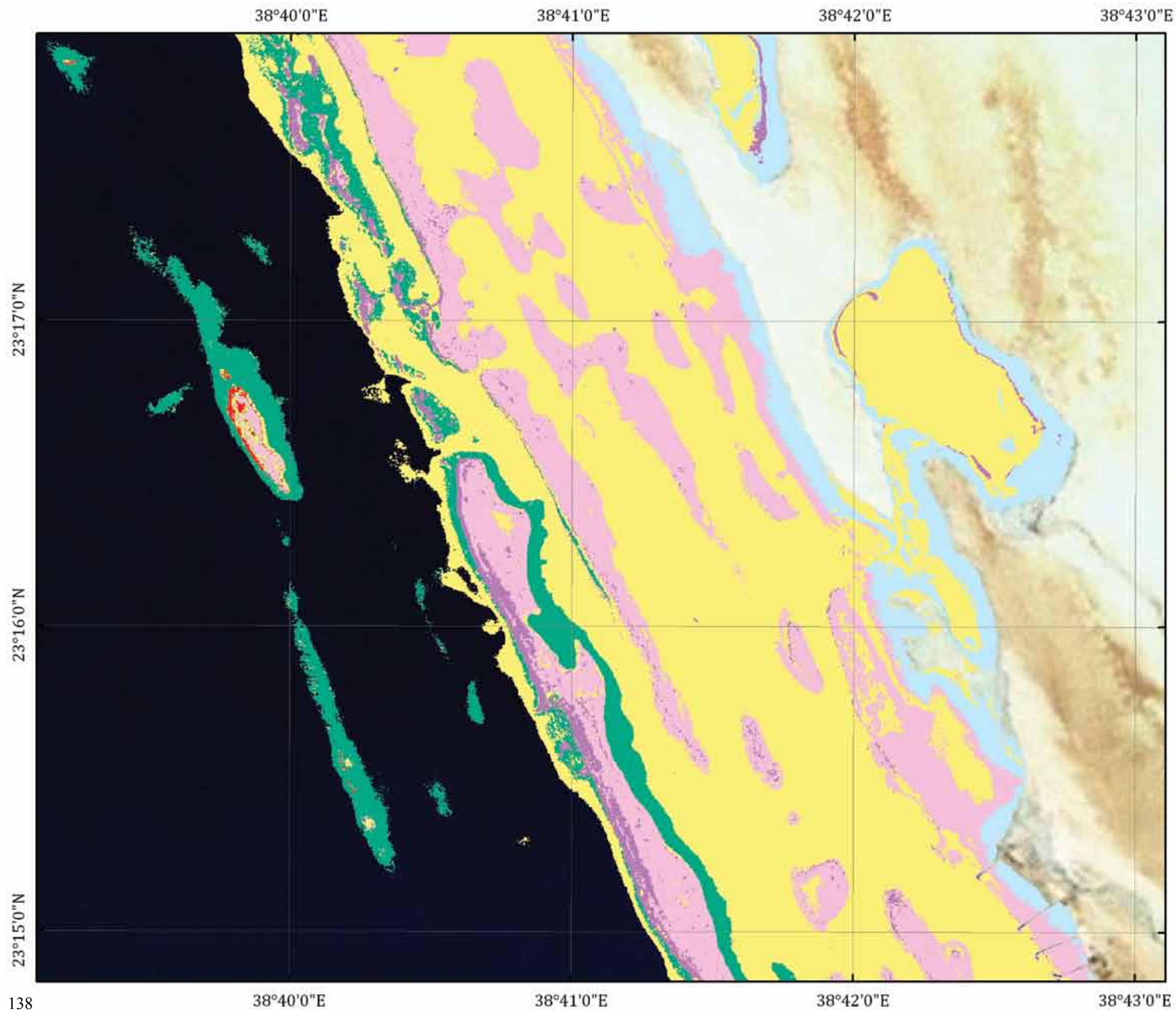


**Yanbu Habitats**

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- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water

1:24,000



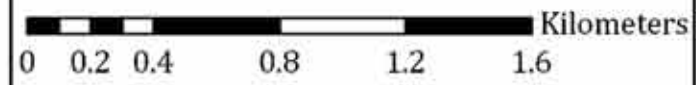


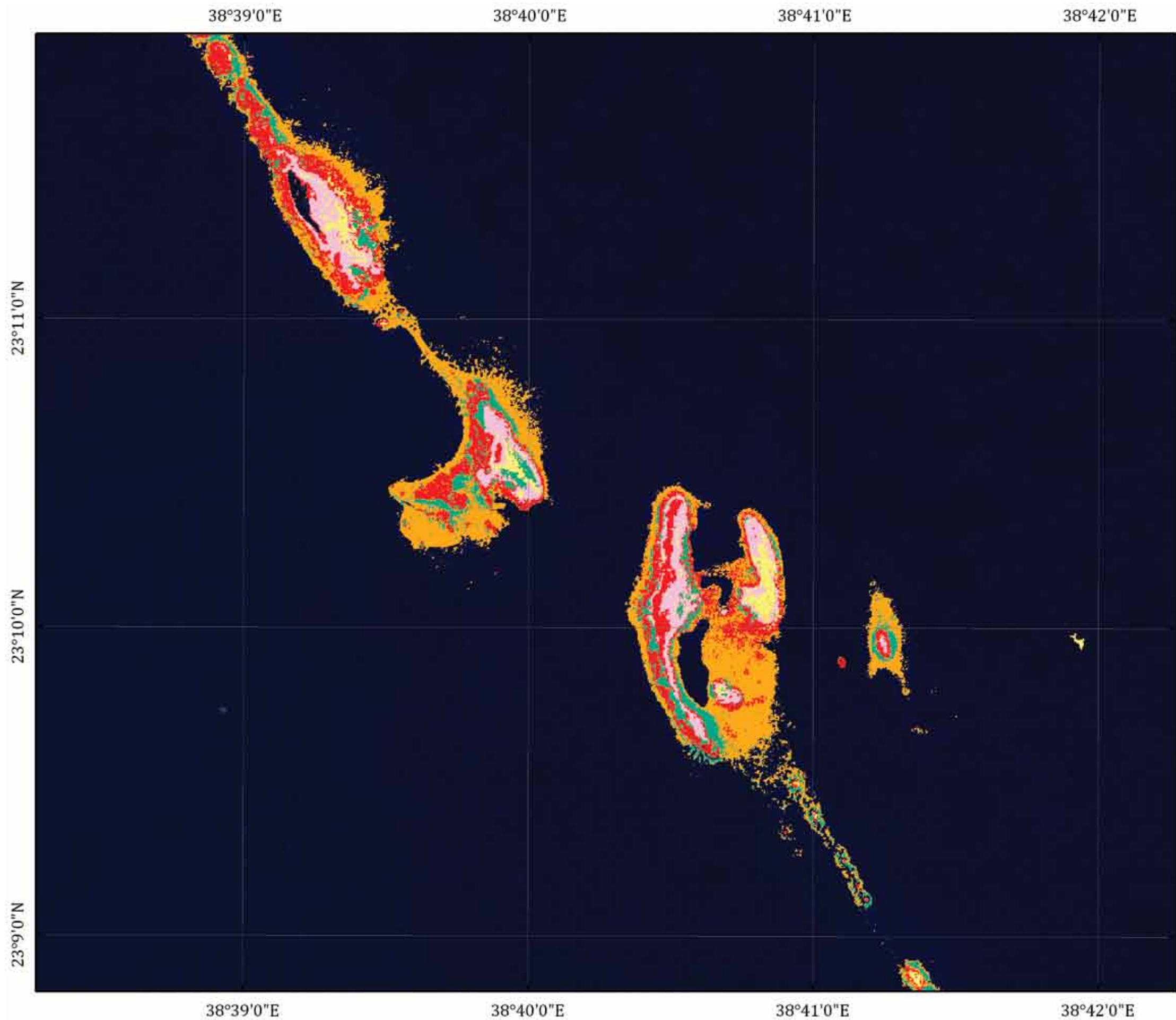
**Yanbu Habitats**

- Windward coral crests
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- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water



**1:24,000**



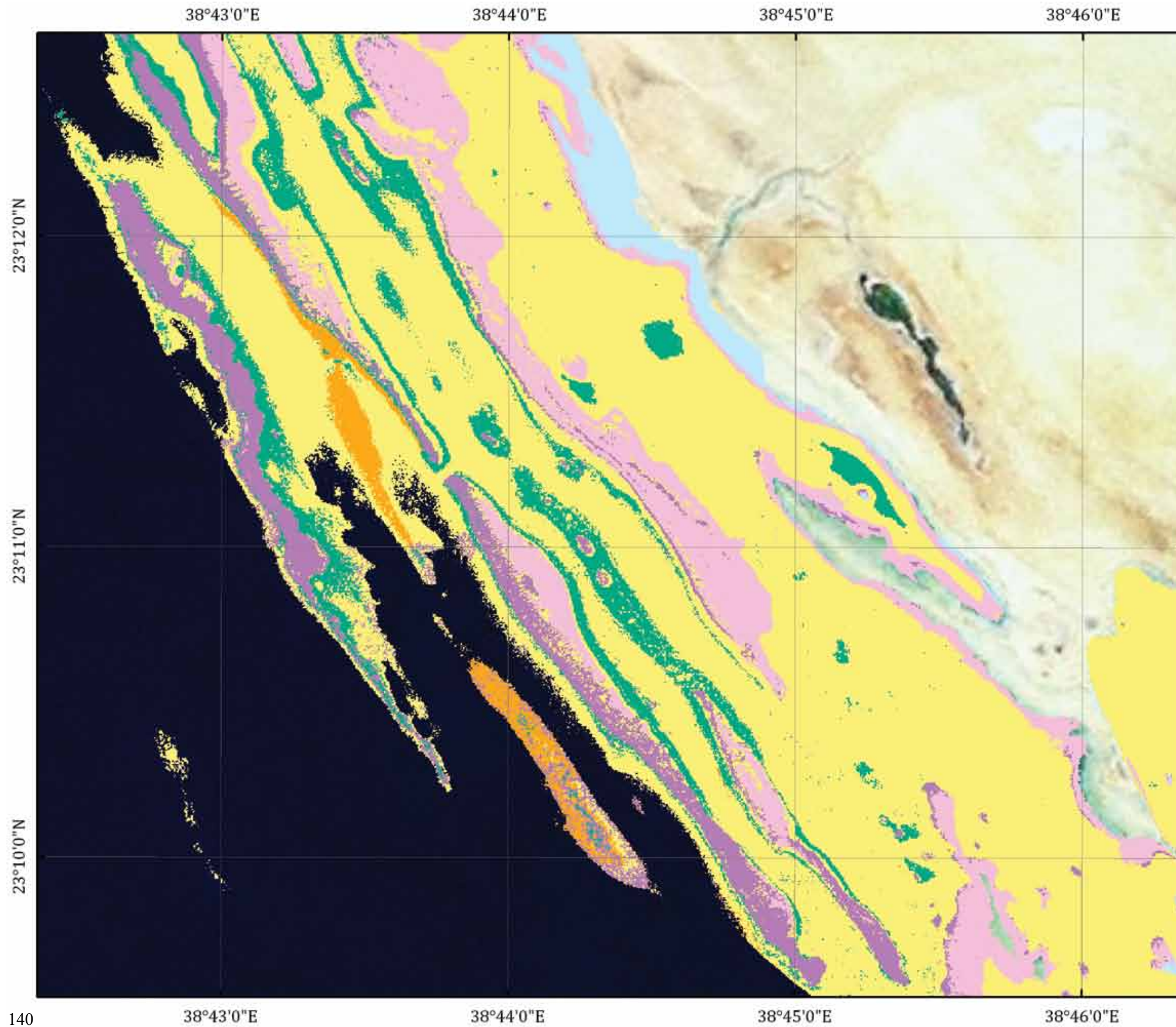


**Yanbu Habitats**

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- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
- Seagrass meadows
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- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water

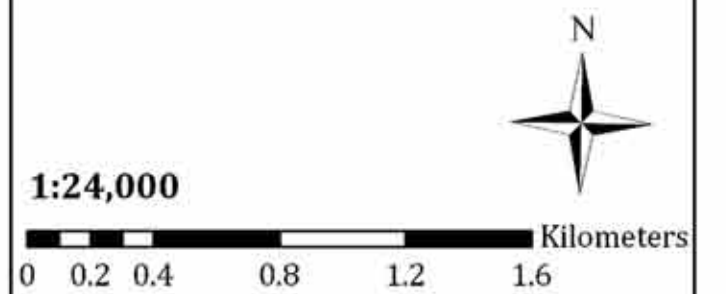
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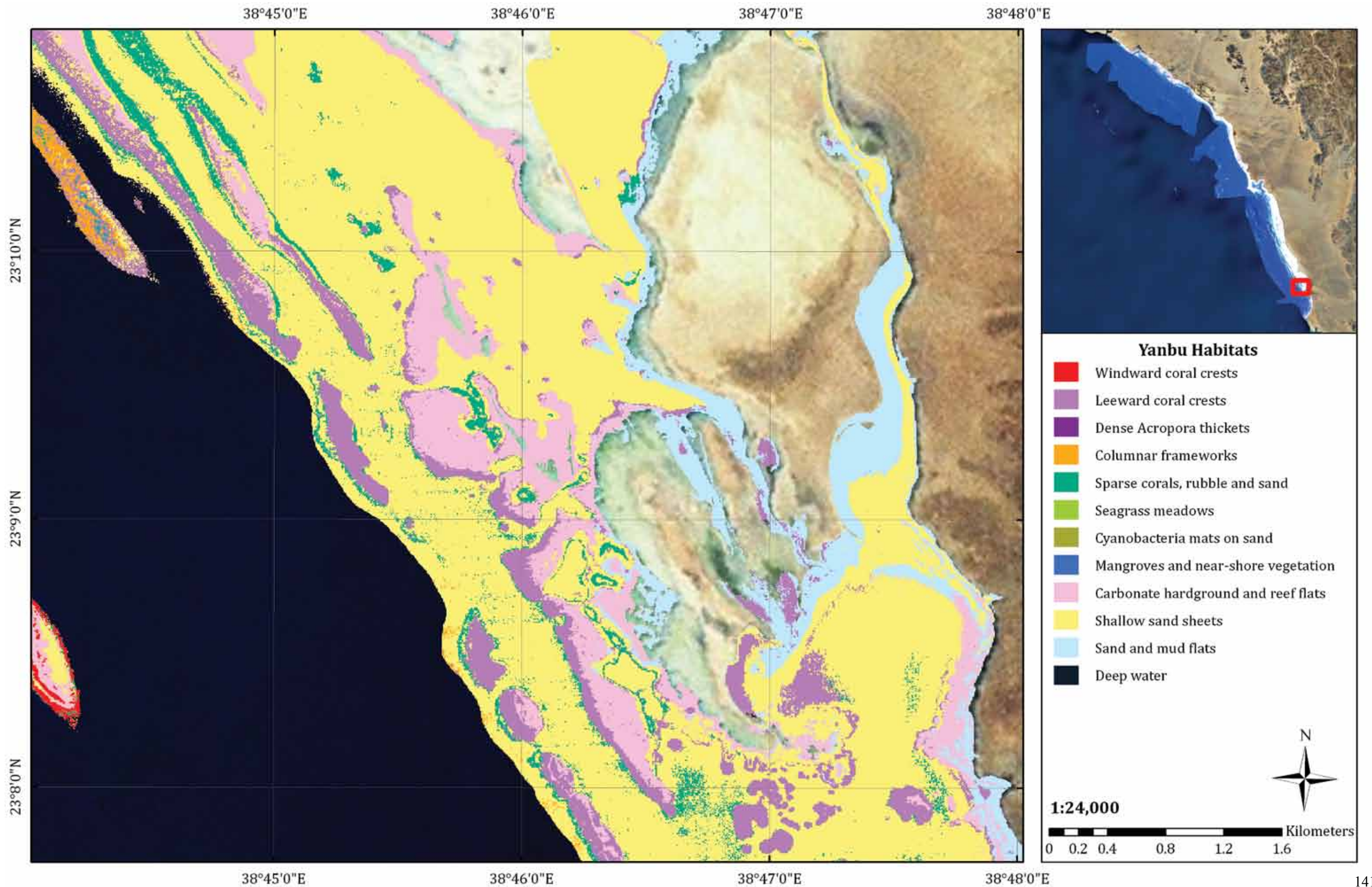


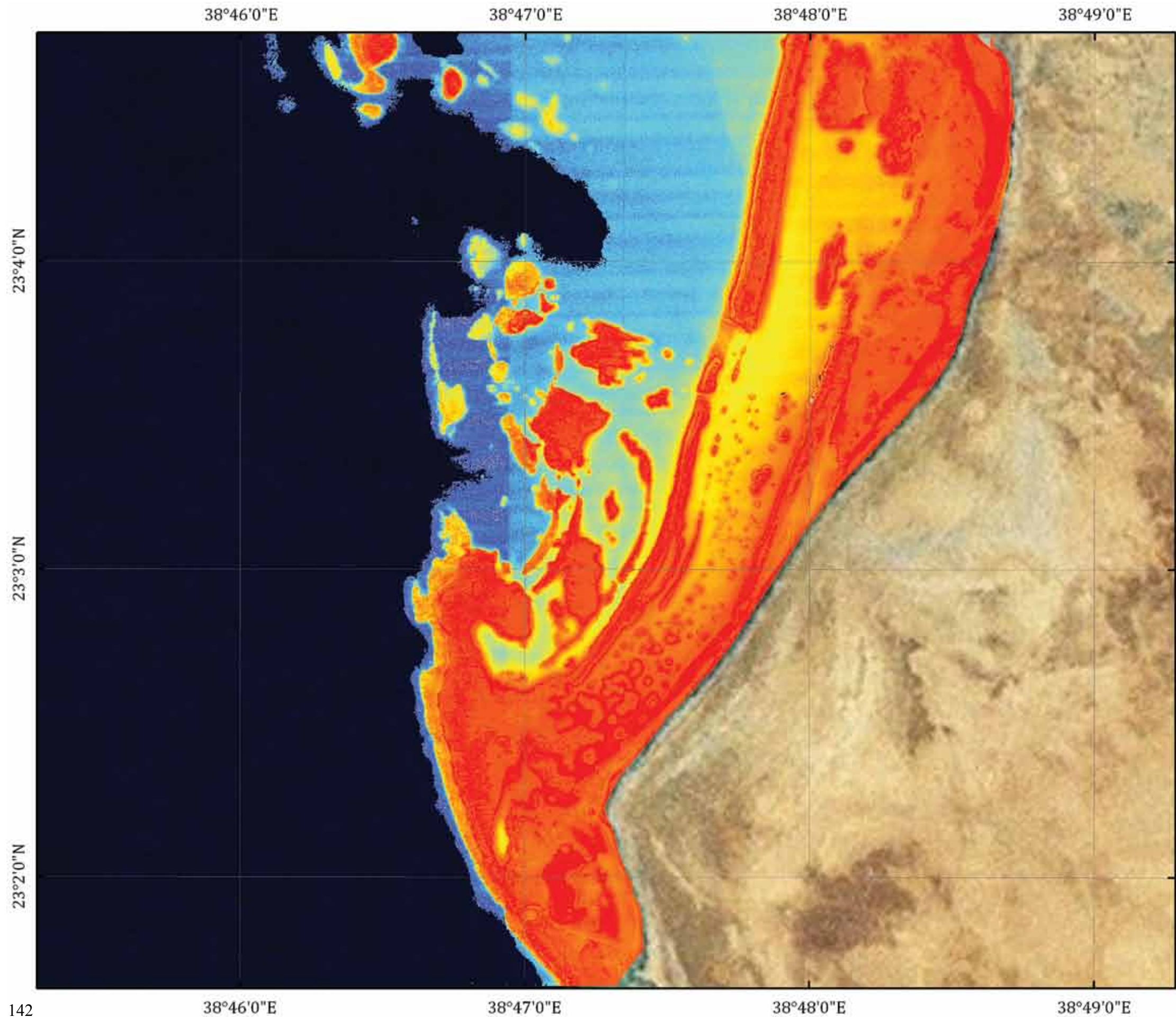


**Yanbu Habitats**

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- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water





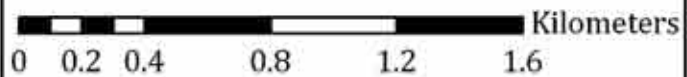


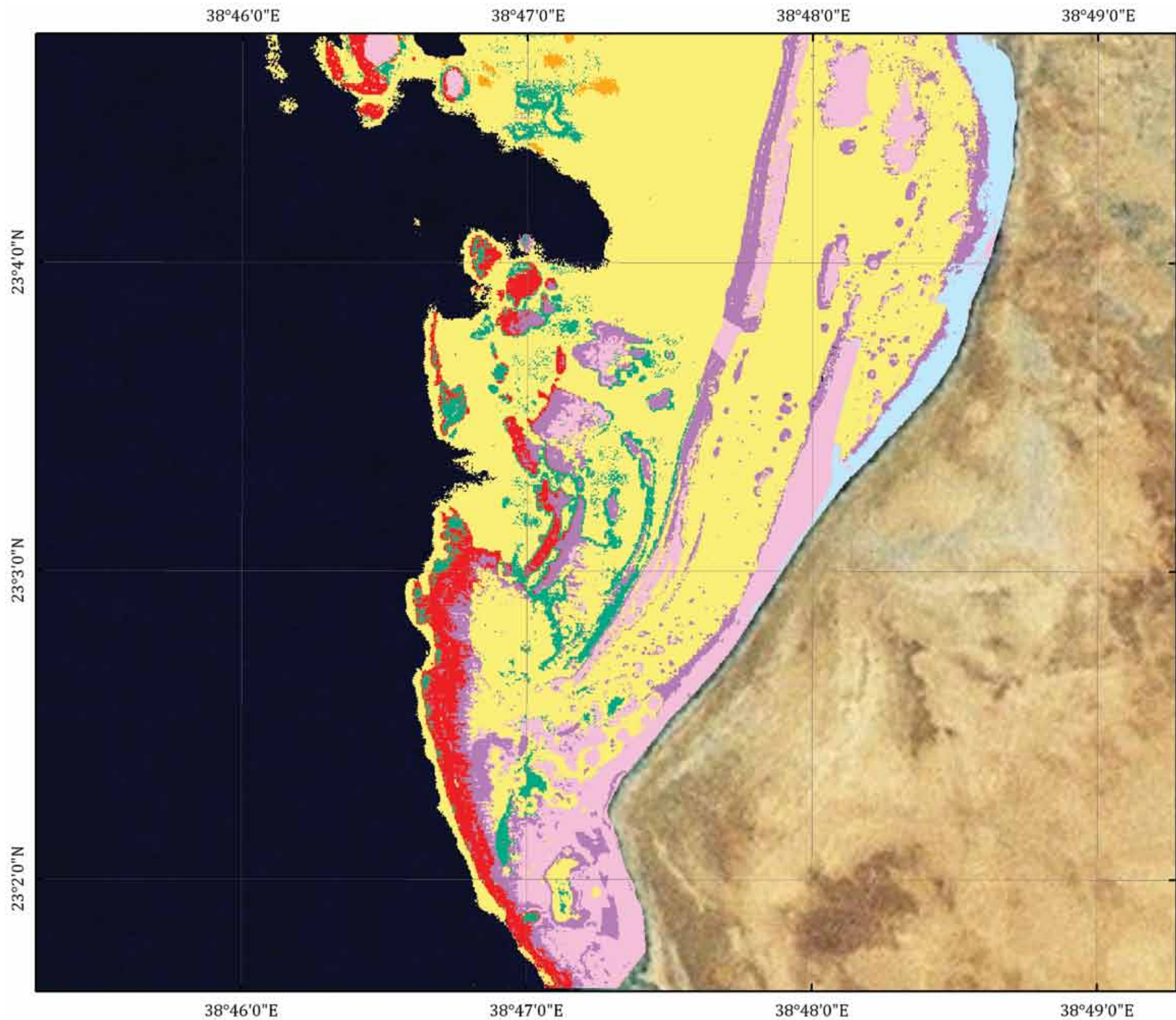
**Yanbu Bathymetry**

Depth, meters

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

**1:24,000**





**Yanbu Habitats**

- Windward coral crests
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- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
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- Sand and mud flats
- Deep water

1:24,000







# Farasan Banks



## Farasan Banks

The Farasan Banks is an extensive area of small islands, shoals, and reef platforms in the southern Red Sea, beginning approximately 230 km south of Jeddah (near Al Lith) and extending nearly 250 km to the Farasan Islands. Unlike other locations in the Red Sea, where fringing reefs predominate and deep water is relatively close to the coastline, the Farasan Banks is characterized by a shallow platform that extends from the coast as far as 100 km offshore. The Farasan Banks covers two degrees of latitude, with complex archipelagos and islands perforated by deep water channels. In addition to the seaward extension of the continental shelf, there are extensive groups of isolated reefs, pinnacles and atoll-like formations separated by deep (500 m+) channels. These extend nearly vertical from the ocean floor to a few meters from the surface. Many of these features partially enclose deep water lagoonal environments with seagrass beds, algal flats, and protected (leeward) coral reef environments. Further inshore, mangroves and grassbeds fringe the coastline.

The northern part of the Farasan Banks has four high pinnacles forming the patch reefs called Dohra, Marmar, El Jedir, and Malathu. The slopes of these pinnacles are nearly vertical and plummet to depths of several hundred meters. These structures are much shorter than ridge reefs (Malathu: 400 m X 140 m). The pinnacles are the surface expression of normal salt diapirs, rising as bulbs or domes and not influenced by normal faults as seen with ridge reefs.



Above: A sandy key, formed of reef-derived carbonate sediments. Without an actively growing reef, such an island would not be formed.

Opposite page, left: Location of the Farasan Banks. Source of basemaps: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

Opposite page, top right: A sandy beach with phytodunes. The latter are dunes stabilized by salt-tolerant plants persisting close to the sea. Along the water-line, a thin layer of beachrock (cemented beach sand) can be seen.

Opposite page, bottom right: Typical Red Sea rocky shoreline. The rocks are limestones and were formed during the Pleistocene. In the foreground, coral fossils can be seen, evidencing a past reef-building episode. Within the intertidal zone, the rock is worn away due to erosional forces (physical and biological) and forms a “notch-and-visor.”



A small offshore rocky island. The well-developed tidal notch is caused by bioerosion. The island platform itself has a Pleistocene core.



A small reef island off Abalat Island. Clearly visible is an erosional notch that surrounds the island. Here, erosion by wave and marine bioeroding organisms, such as sea urchins, has eaten away on the carbonate mass. The bulk of the island is made up by deposits from a relative sealevel highstand in the Pleistocene.



Reef-derived rubble on an offshore Red Sea beach. Most fragments are coral branches; the larger, clearly angular fragments are pieces of beachrock that were transported from a nearby beach.



Shallow reef flat community with patches of corals separated by narrow sand channels.



Examples of coral reef habitats within the Farasan Banks.

Top left: Base of a shallow leeward reef with massive *Porites* colonies, tabular acroporids and soft corals, at 11 m depth.

Bottom left: Dense assemblage of *Porites lutea* colonies on a midshelf reef, at 10 m depth.

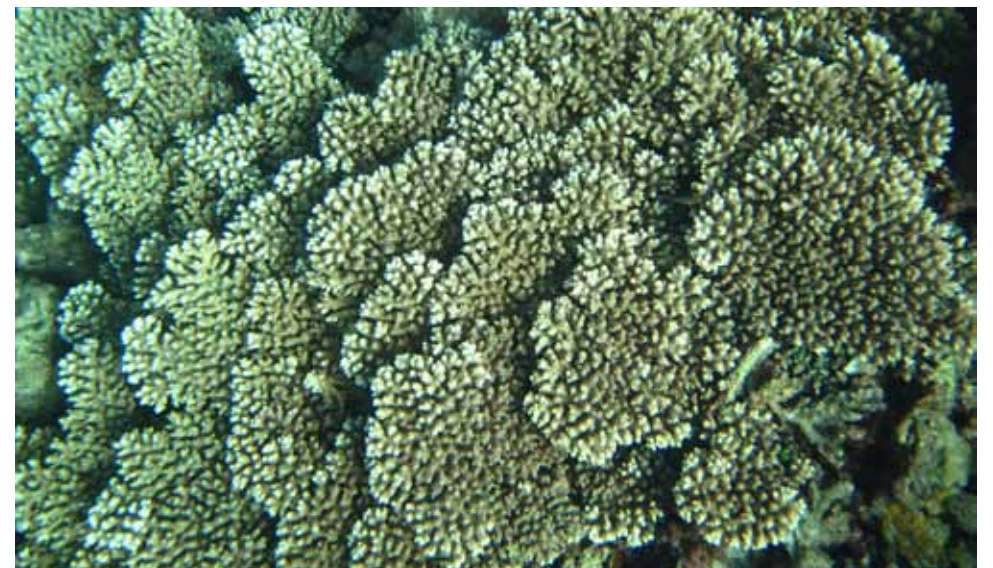
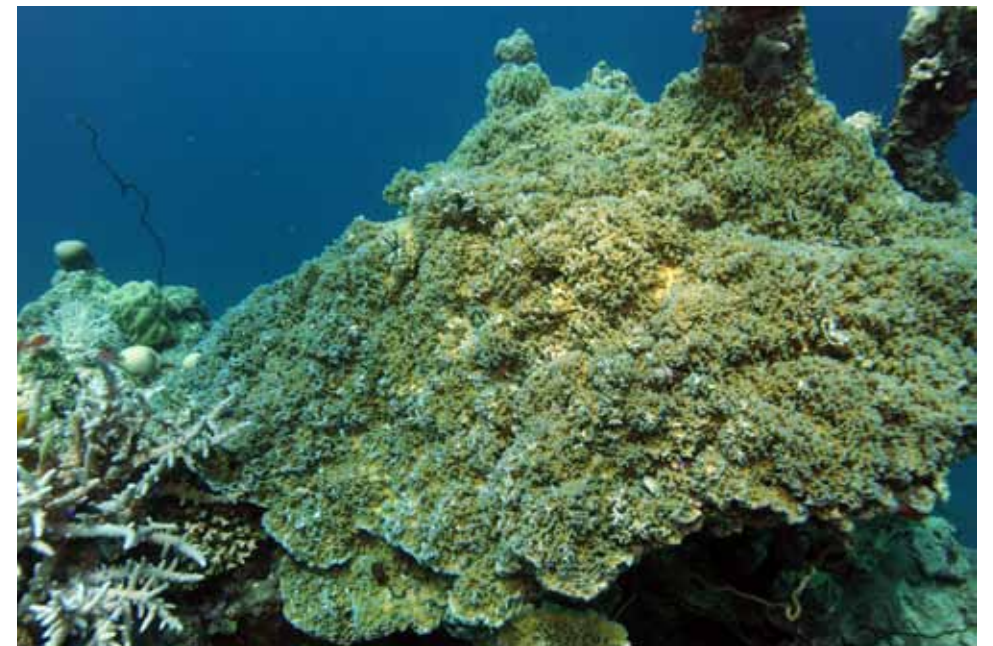
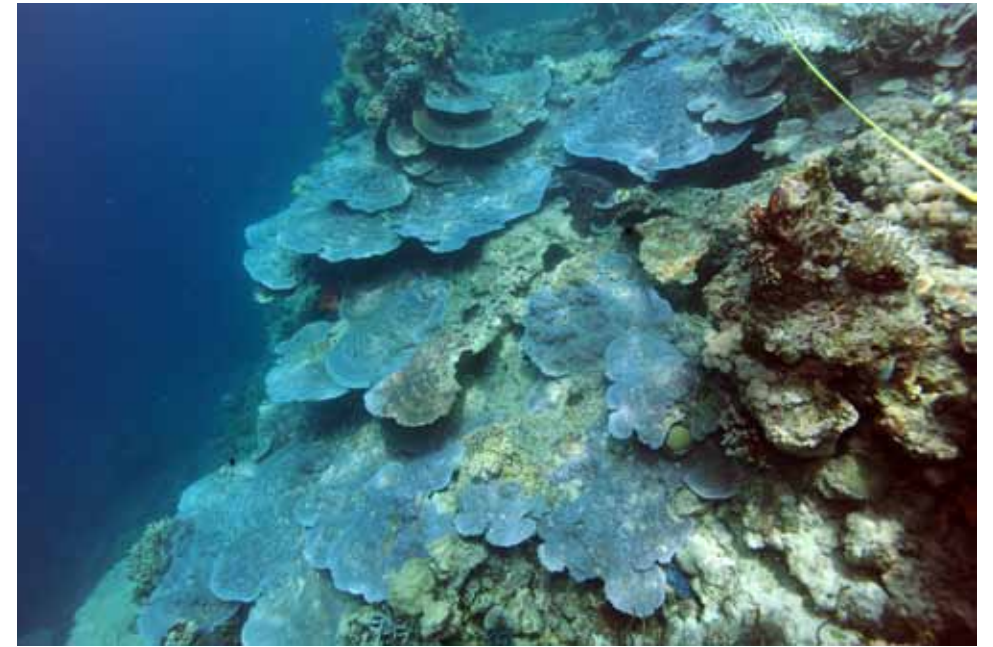
Top middle: Shingle-like plates of *Montipora* on a columnar *Porites* framework.

Bottom middle: Shallow leeward reef with a dense *Acropora* thicket intermixed with *Porites lutea* and other species, at 9 m depth.

Top right: Reef slope at 15 m depth on an exposed windward midshelf reef colonized by plating *Montipora*.

Middle right: Large *Montipora* colony overgrowing a dead colony of *Porites*.

Bottom right: Encrusting acroporids on an exposed reef crest adjacent to the drop-off.

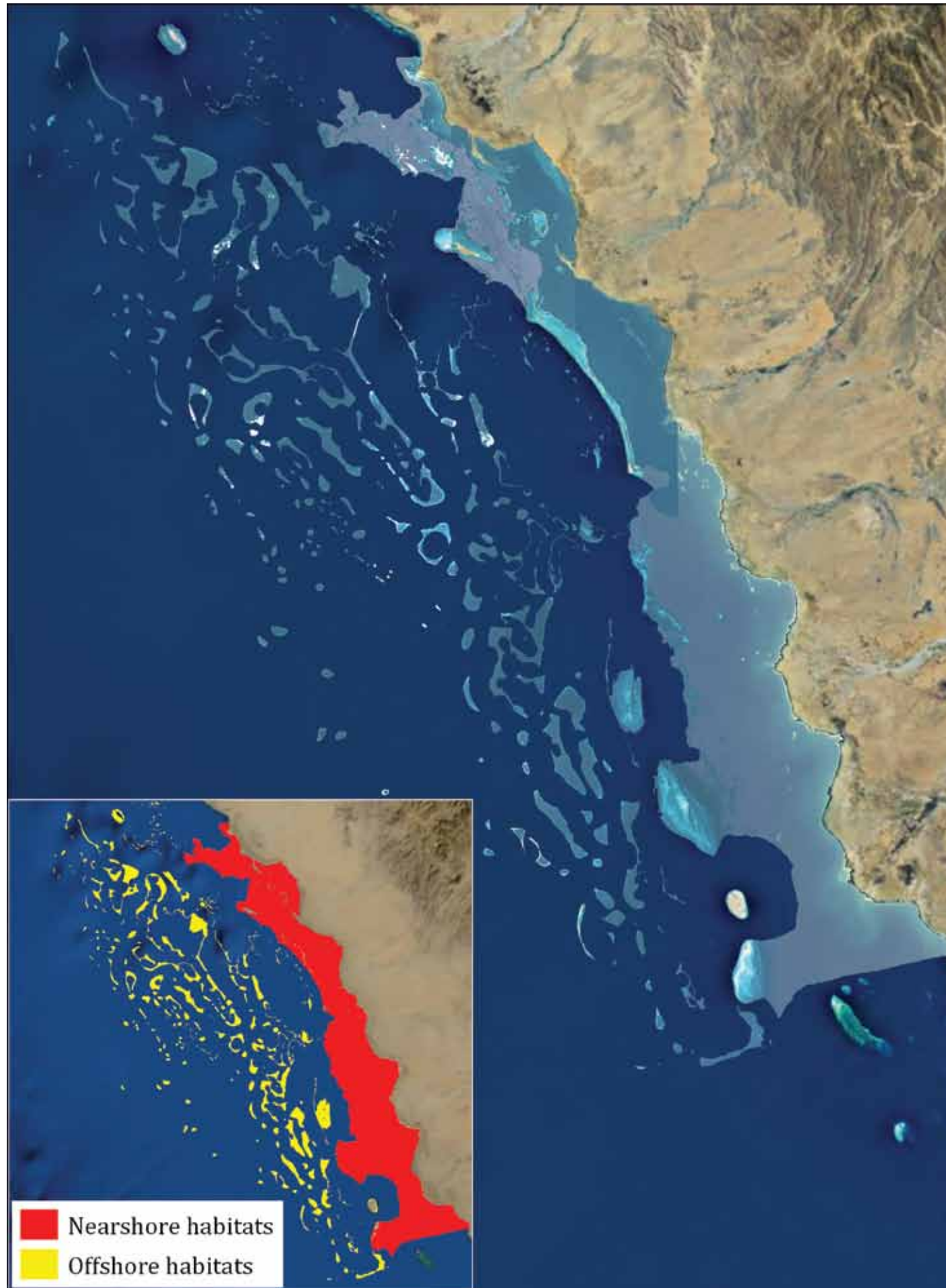


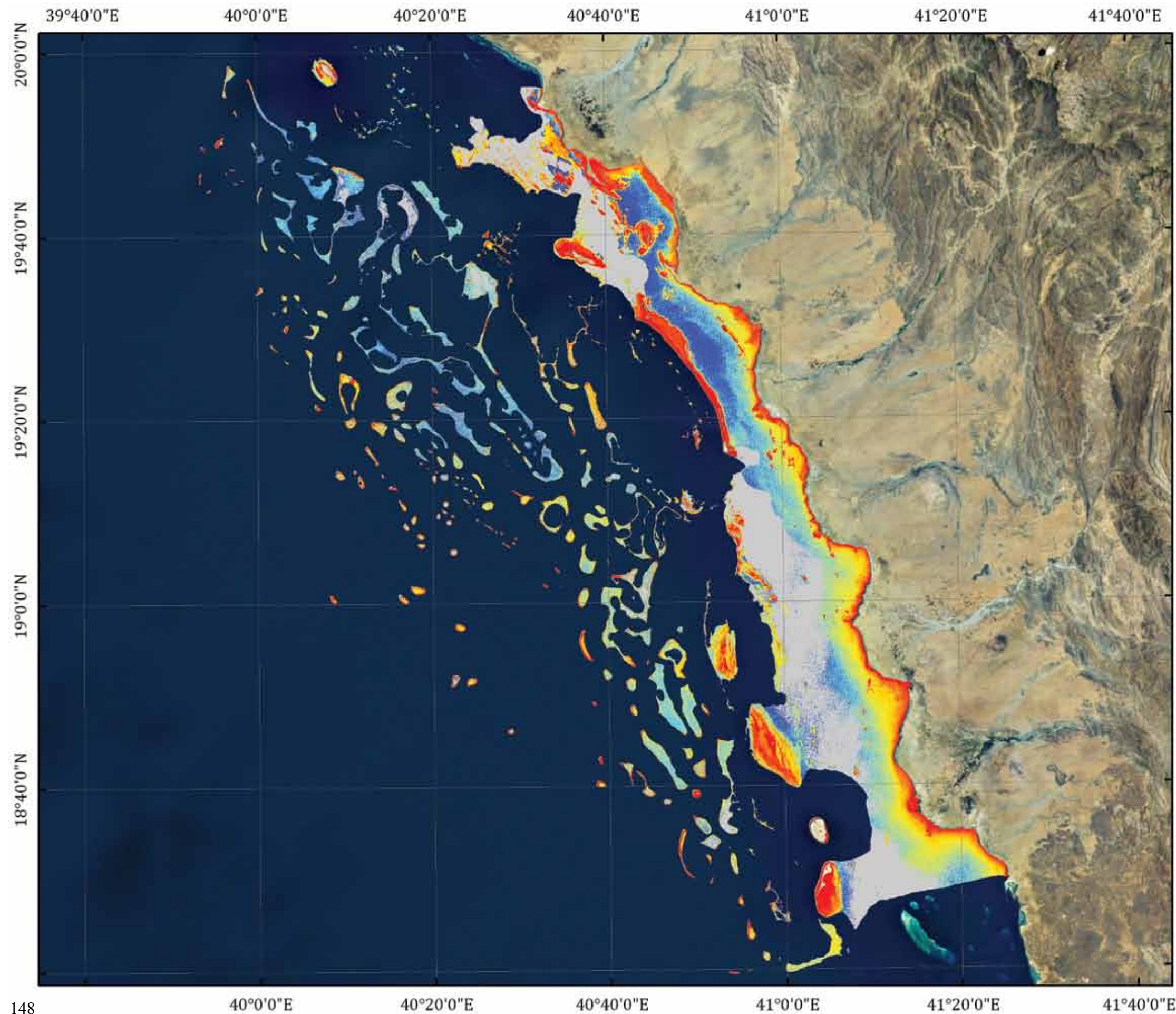
## Farasan Banks Imagery and Habitat Maps

Satellite imagery, bathymetry, and habitat maps for Farasan Banks are illustrated on pages 147-227. QuickBird multispectral satellite imagery of the Farasan Banks (left), bathymetry (page 148), and a resulting habitat map for the same area (page 149) are shown at a scale of 1:800,000. A regional locator map, bathymetric map, and habitat map, at a scale of 1:325,000, are shown for the north on pages 151-153, northcentral on pages 175-177, southcentral on pages 195-197, and south on pages 211-213. Higher resolution habitat maps (1:24,000) and bathymetric maps for representative areas within the Farasan Banks are shown on subsequent pages. Each of the nine 1:24,000 scale bathymetric maps included in this section is on the left (even-numbered) page and the habitat map for the same area is shown on the right (odd-numbered) page. Habitat maps start in the north and work progressively southward. These include habitats associated with the barrier reef, lagoonal environments and nearshore habitats. Source of terrestrial basemap imagery used in all habitat and bathymetric maps is: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

A total of 4,160 sq km was mapped and subdivided into 15 habitat classes with areas below 25 m depth (deep water) depicted in dark blue. The aerial coverage of each habitat is presented in the table for nearshore areas, which extend from 0.5-1.5 km offshore (depicted in red in inset on the left), and offshore areas (depicted in yellow in the inset). The most extensive habitat types were shallow sandsheets and deep lagoonal sands, which made up over 70% of all marine habitats and over 80% of the nearshore habitats. Corals were found in six habitat types, covering an area of about 900 sq km. Hardground areas with isolated corals constitute an additional 380 sq km of the bank, while soft-bottom habitats with seagrass, algae, and cyanobacteria occupied 13 sq km. Nearshore areas included some coral habitats with mangroves, shallow sand and mudflats, and algal areas covering about 184 sq km.

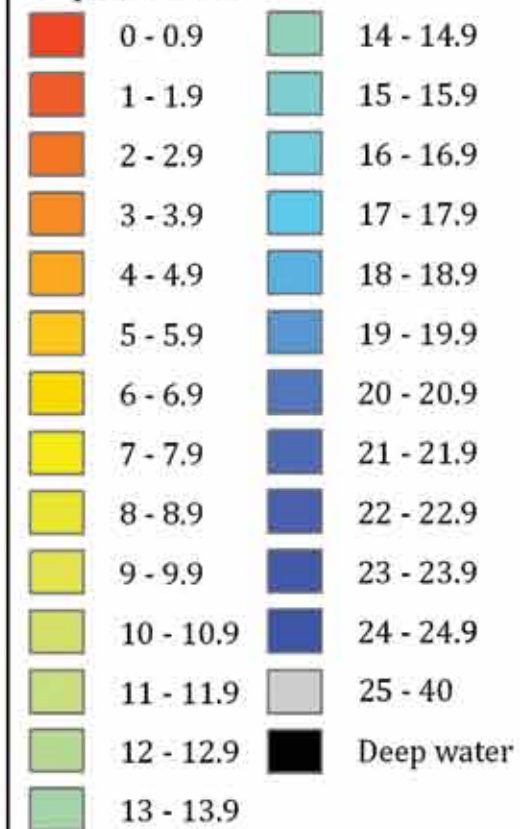
Farasan Banks Habitats	Total area (sq km)	% region total	Nearshore (sq km)	Offshore (sq km)
Reef walls and drop-offs	27.69	0.70	0.71	26.98
Windward coral crests	93.28	2.20	5.30	87.98
Leeward coral crests	38.20	0.90	23.66	14.54
Dense <i>Acropora</i> thickets	1.01	0.05	1.01	0.00
Columnar frameworks	465.02	11.20	26.24	438.78
Sparse corals, rubble, and sand	281.12	6.80	81.75	199.37
Seagrass meadows	31.57	0.80	31.49	0.08
Macroalgae, sponges, sandy hardgrounds	31.94	0.80	29.01	2.93
Cyanobacteria mats on sand	3.31	0.10	3.08	0.23
Mangroves and nearshore vegetation	5.53	0.10	5.21	0.32
Scoured channels	0.02	0.00	0.00	0.02
Carbonate hardground and reef flats	69.17	1.70	21.94	47.23
Shallow sand sheets	1893.20	45.50	1714.07	179.13
Deep lagoonal sands	1074.77	25.80	1074.77	0.00
Sand and mud flats	143.63	3.50	142.31	1.32
<b>TOTAL AREA MAPPED</b>	<b>4159.46</b>	<b>100</b>	<b>3160.55</b>	<b>998.91</b>



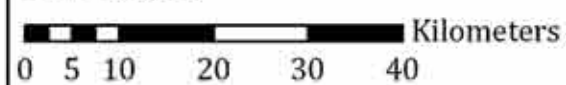


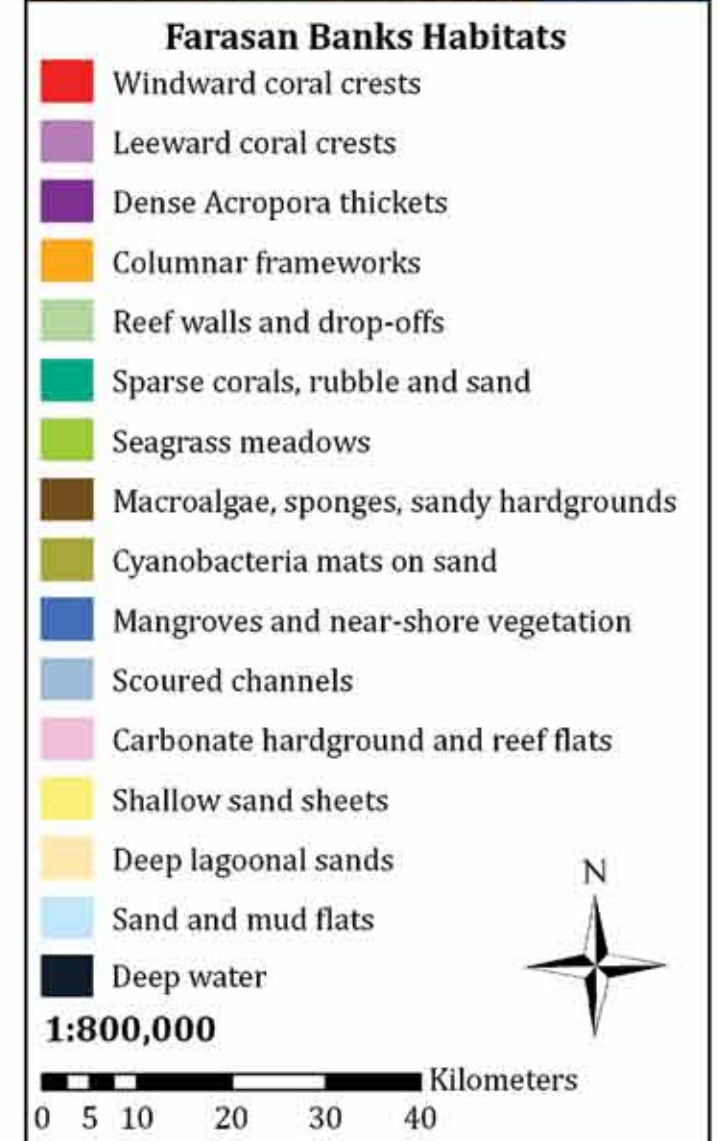
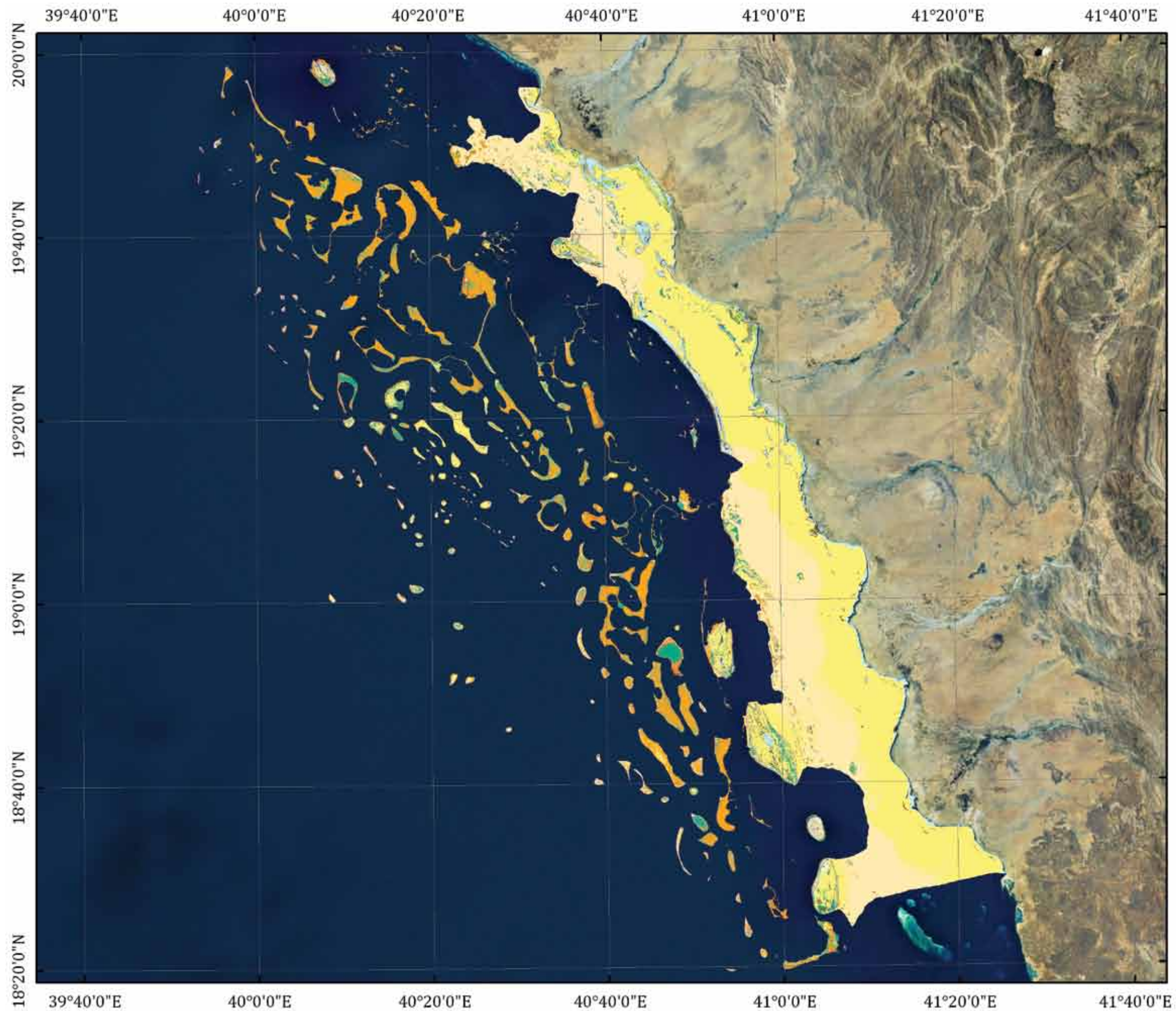
**Farasan Banks Bathymetry**

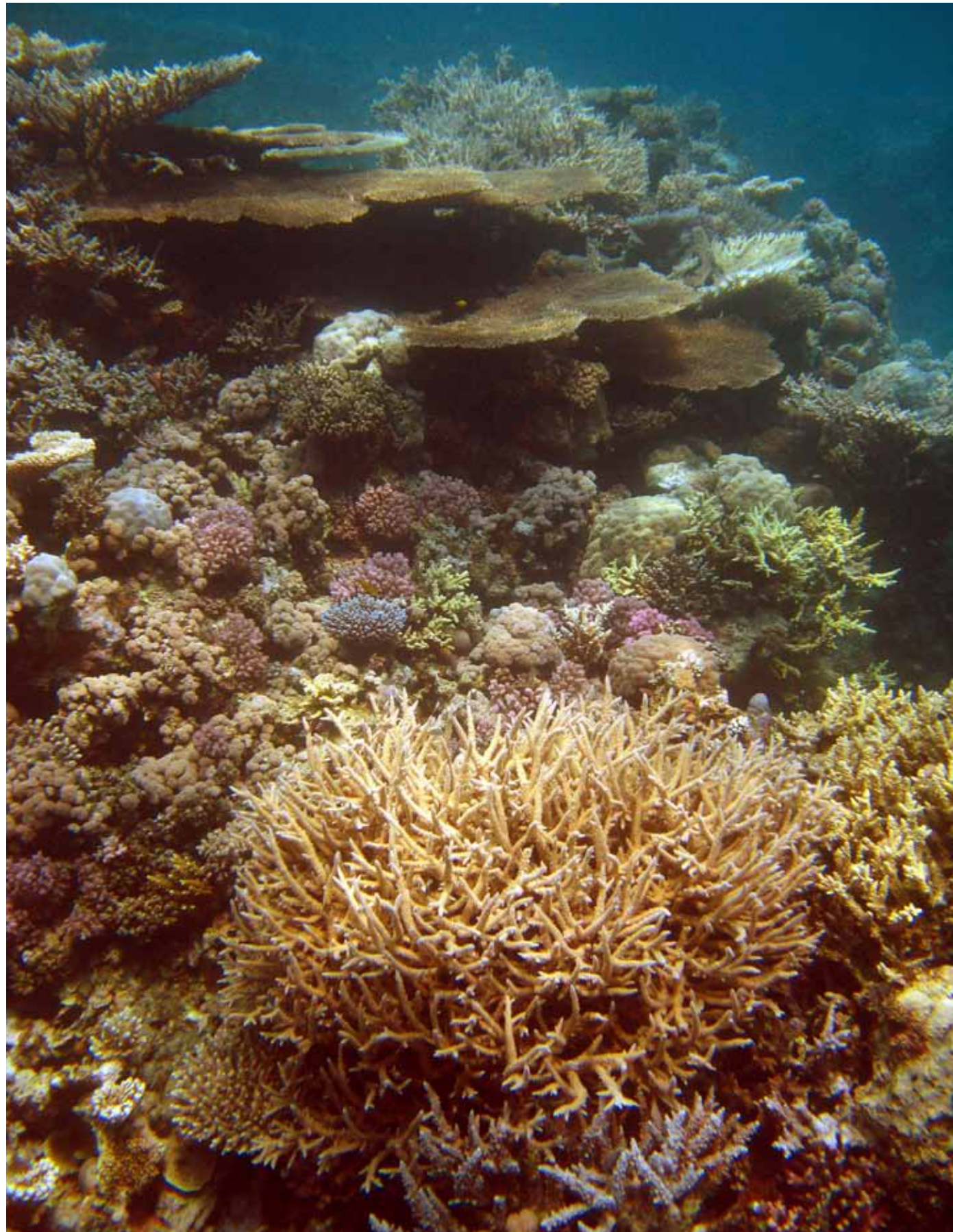
Depth, meters



**1:800,000**







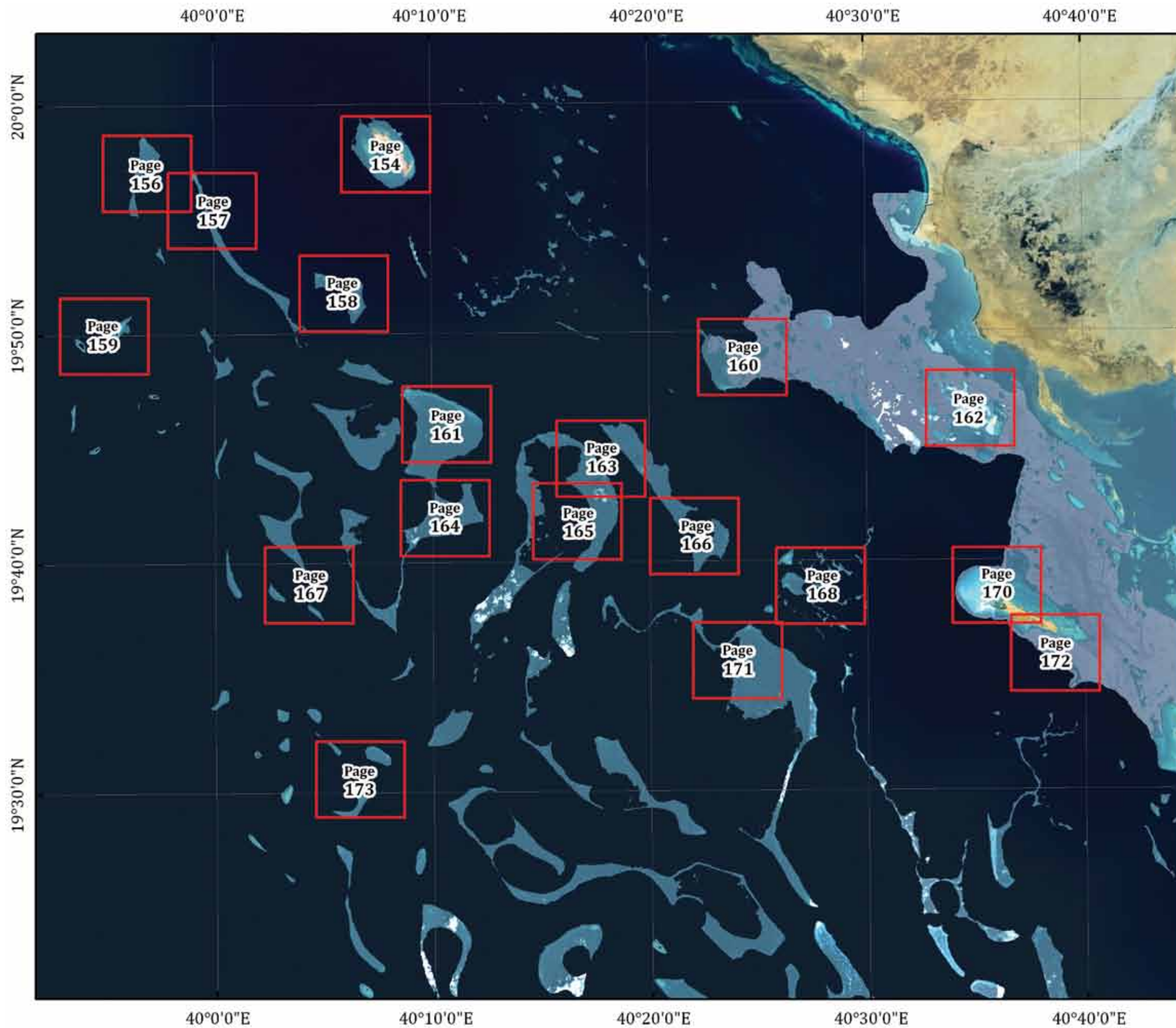
Reef slope on a midshelf reef. The community is dominated by branching, digitate, and table acroporids and small massive colonies of *Porites lutea*.



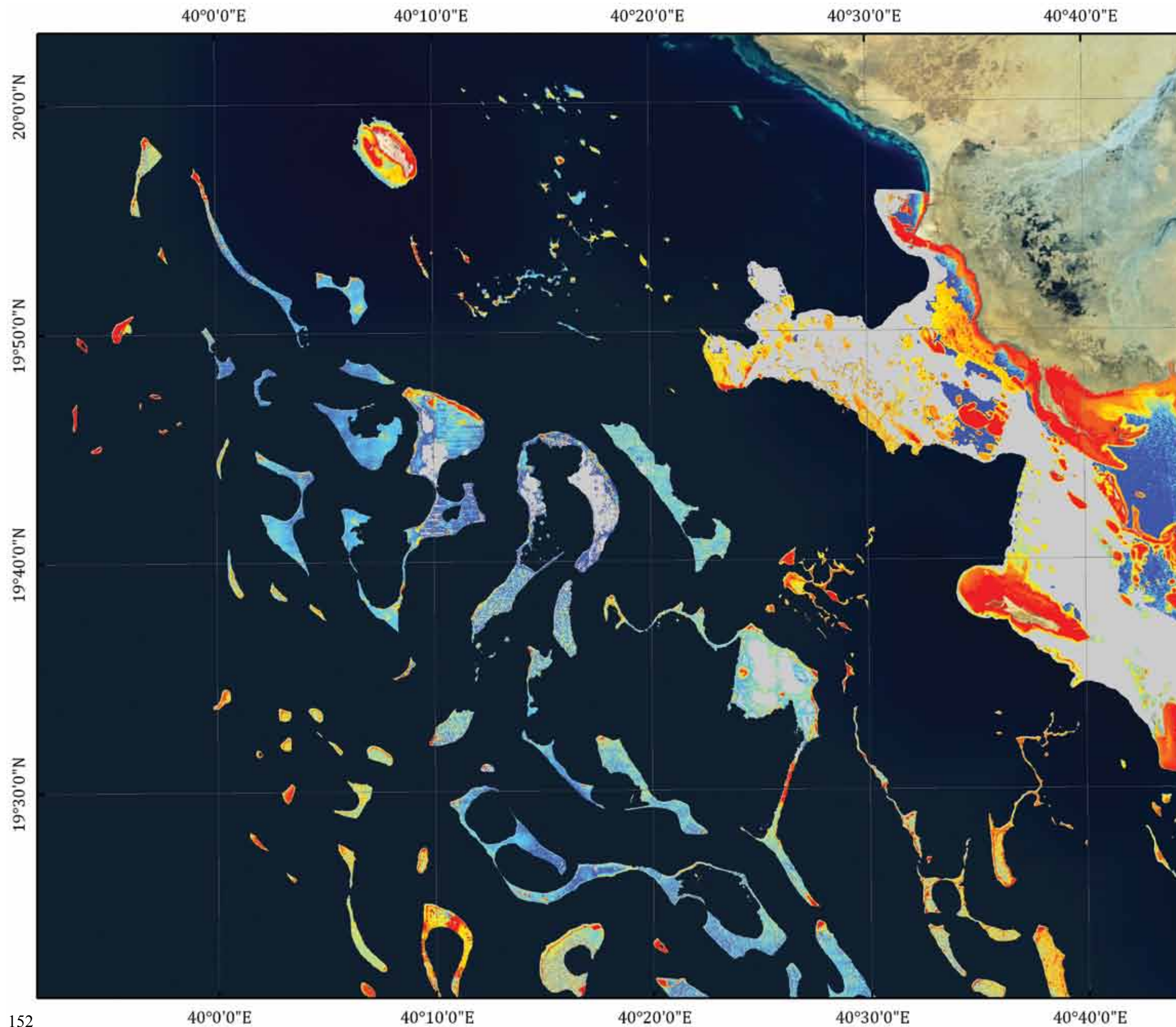
Unusually large lobate colonies of *Lobophyllia hemprichii*, some over 5 m in diameter, were found in a lagoonal habitat of an offshore reef.



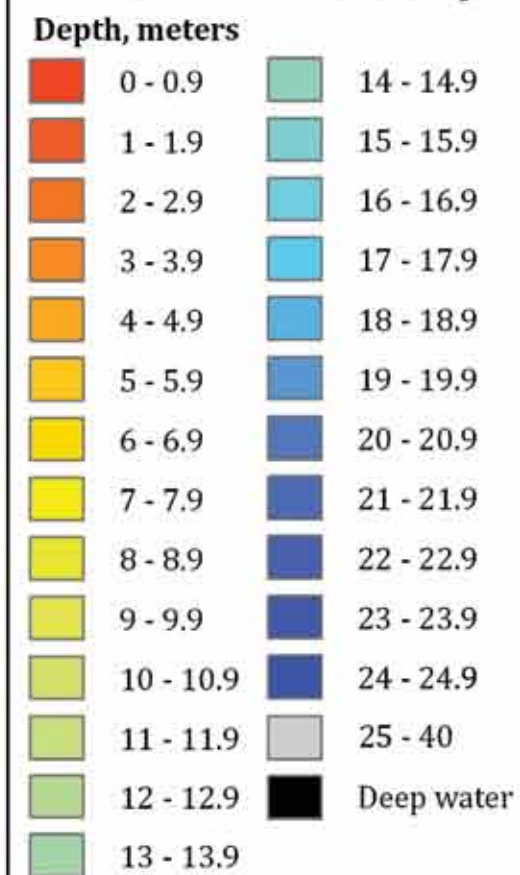
*Goniopora* can form large colonies several meters in diameter, such as this colony of *G. columna* seen on a shallow midshelf reef.





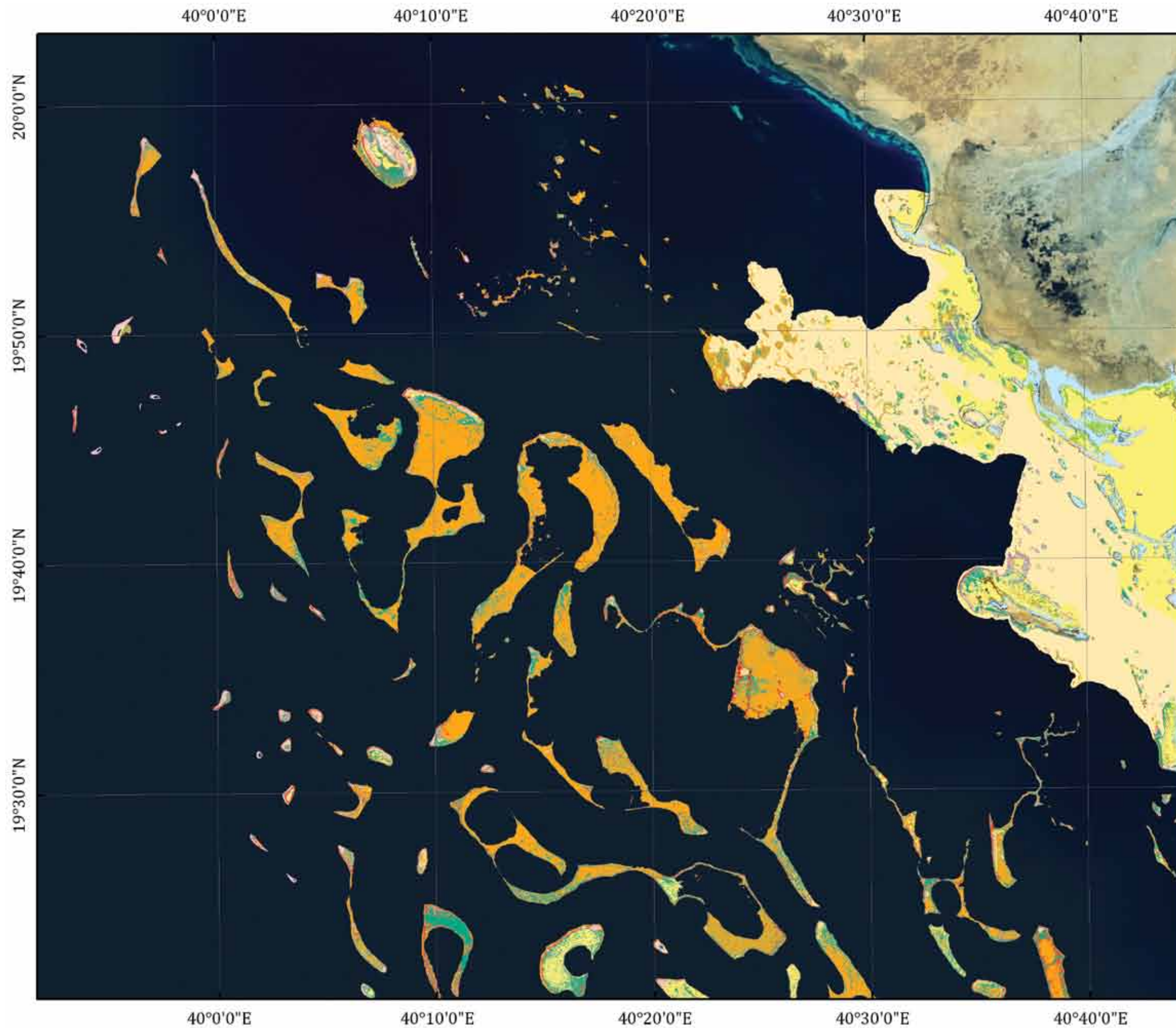


**Farasan Banks Bathymetry**



**1:325,000**



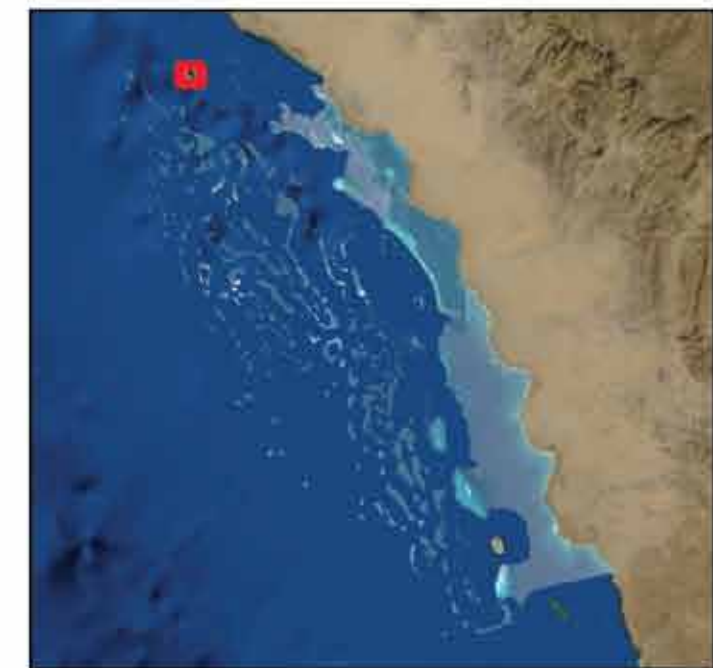
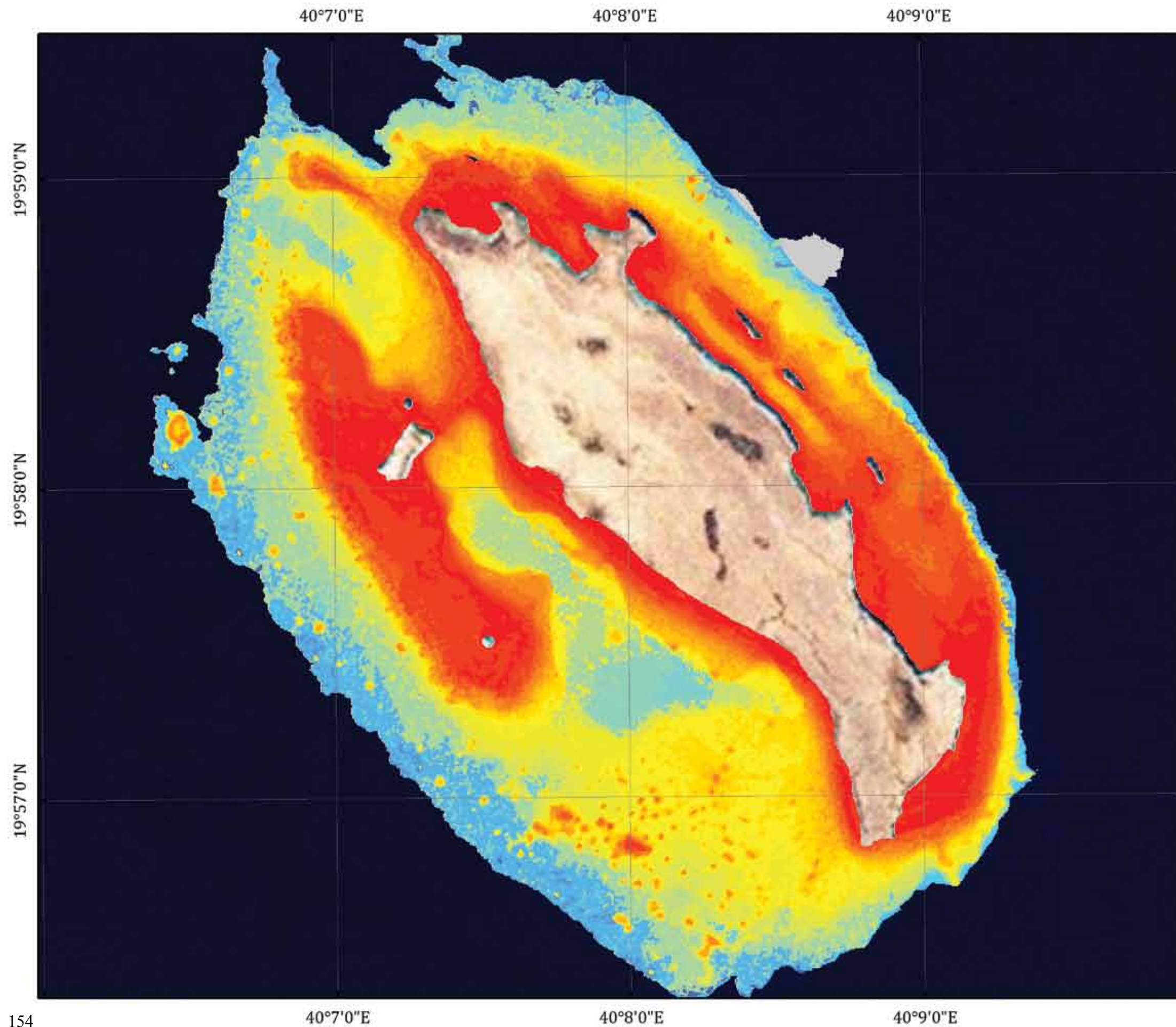


**Farasan Banks Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
- Macroalgae, sponges, sandy hardgrounds
- Cyanobacteria mats on sand
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- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:325,000**





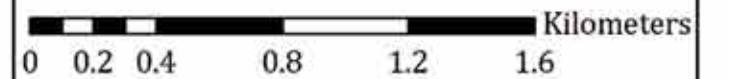
**Farasan Banks Bathymetry**

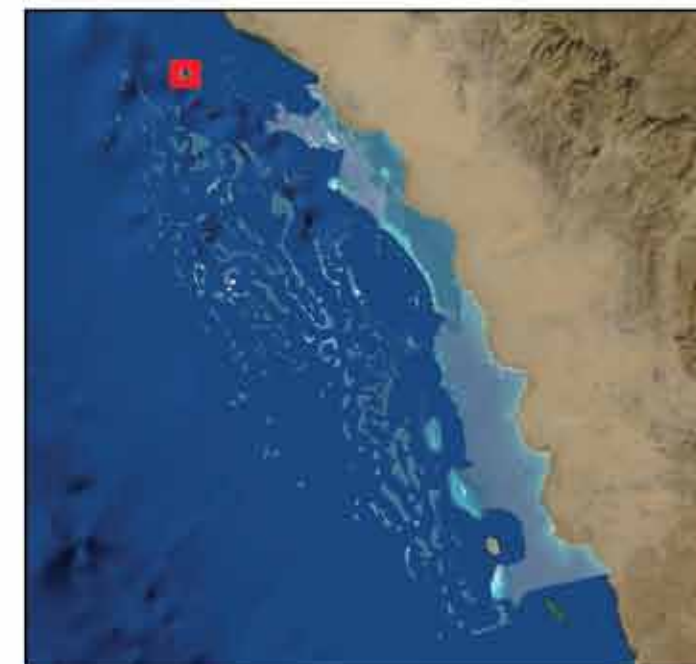
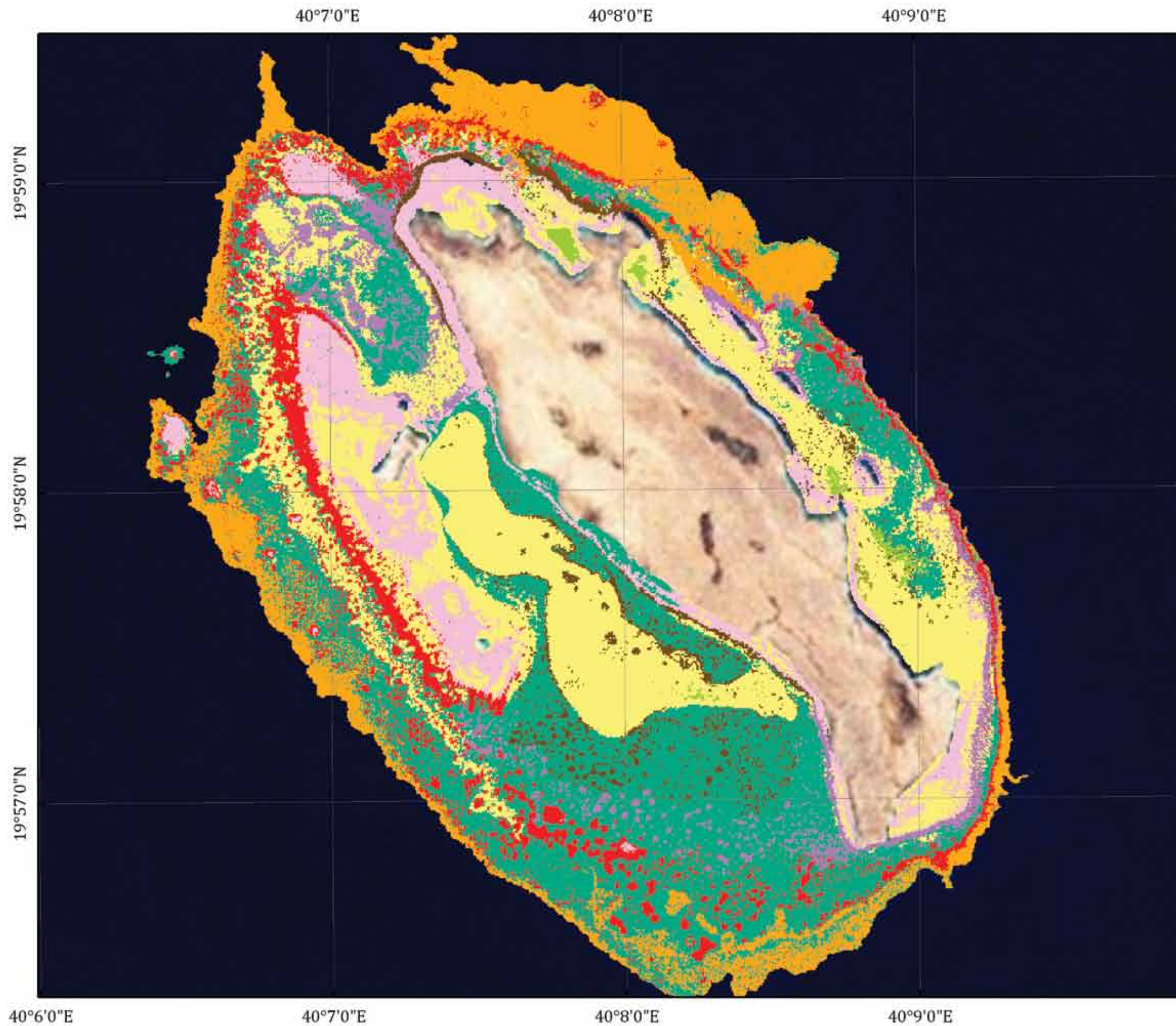
Depth, meters

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	



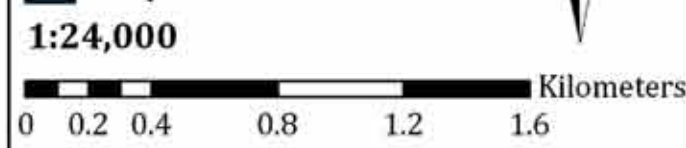
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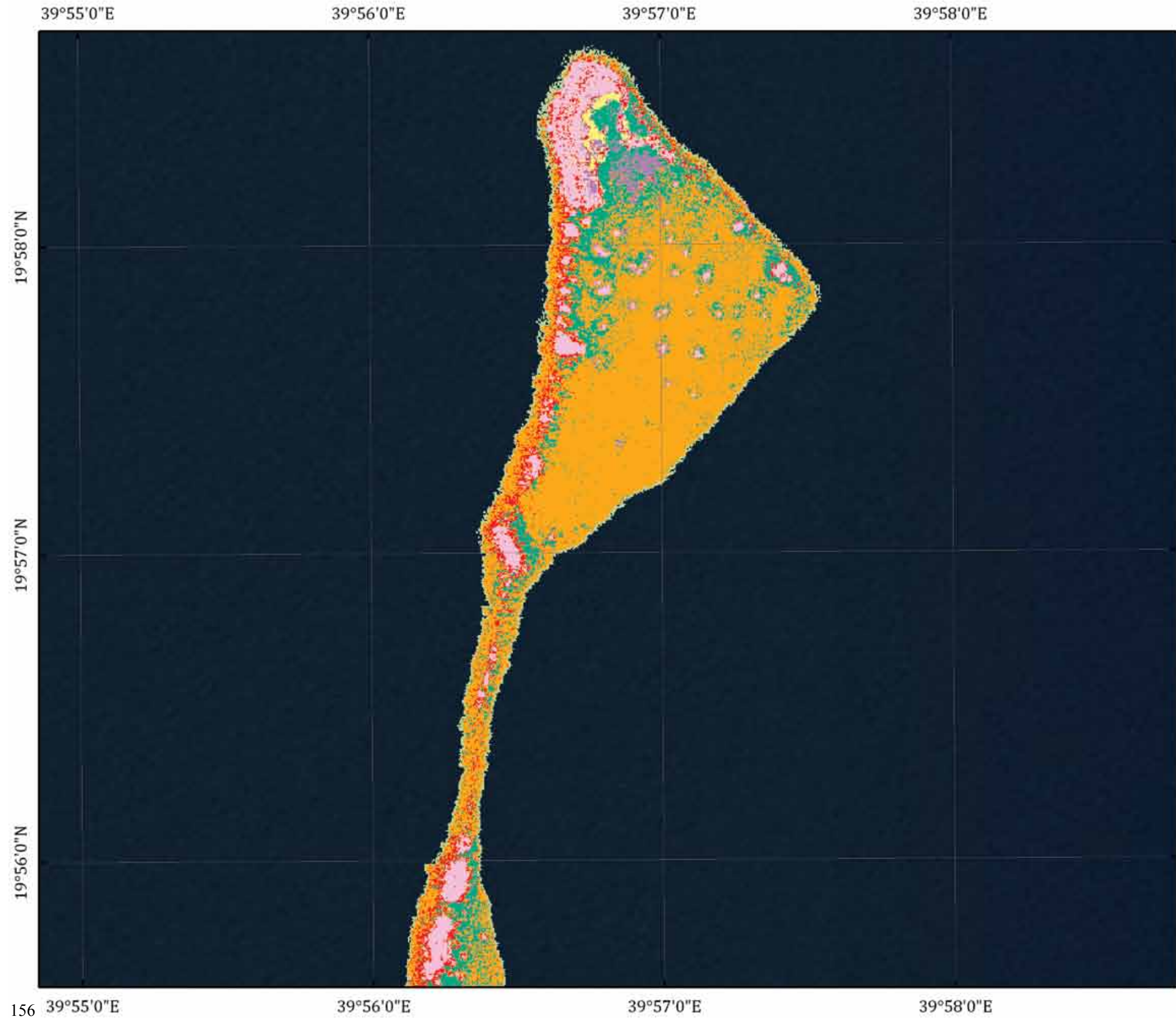
**Farasan Banks Habitats**

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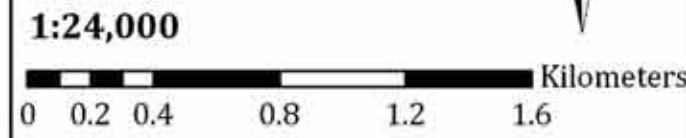
40°6'0"E      40°7'0"E      40°8'0"E      40°9'0"E

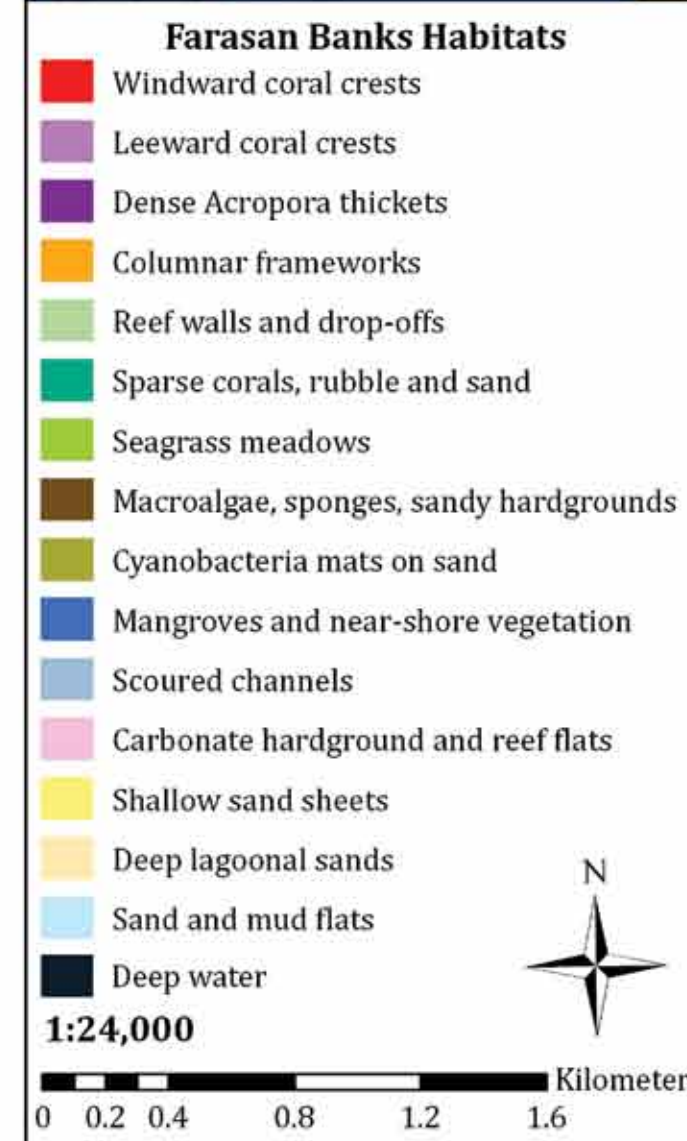
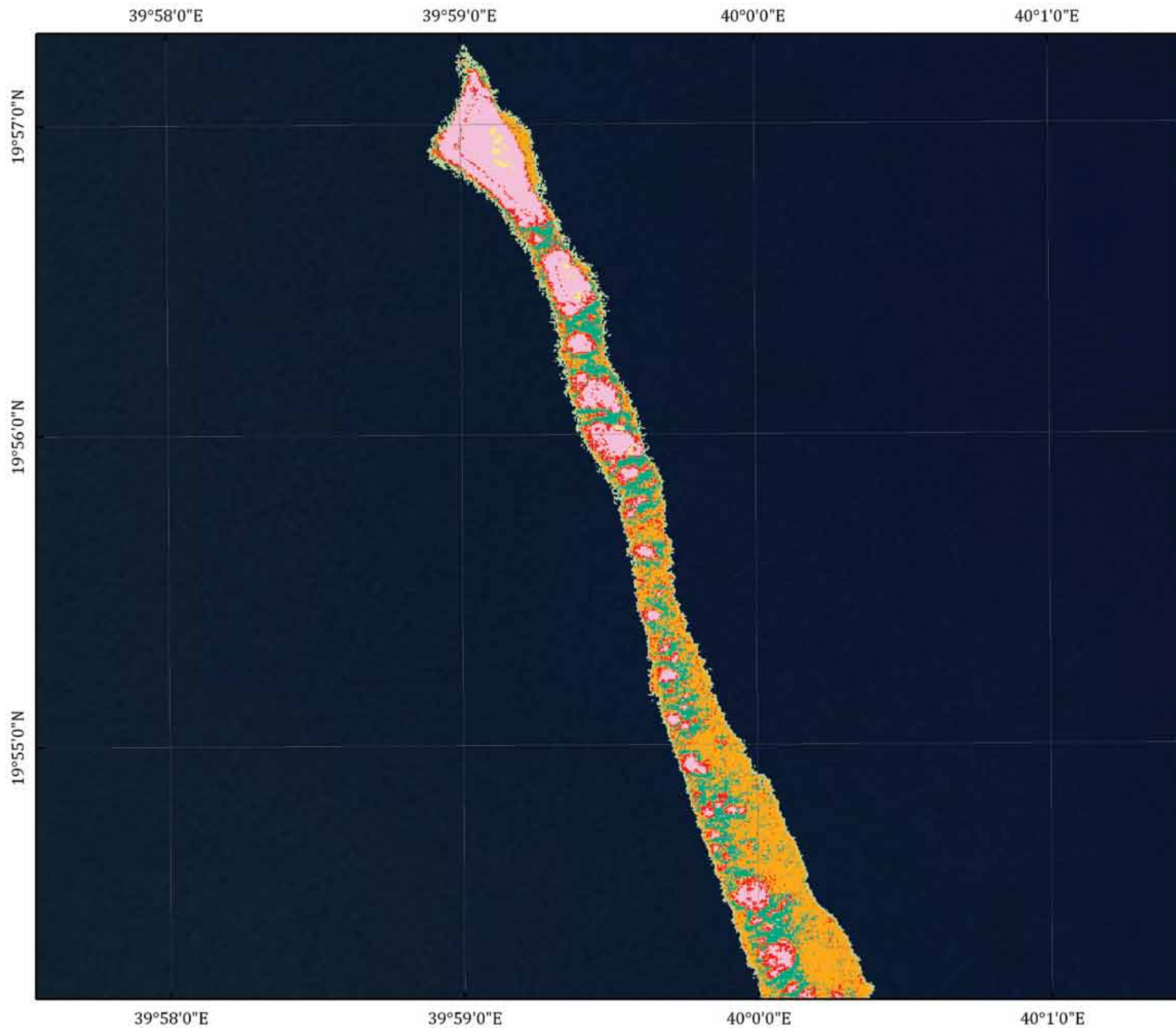
19°59'0"N  
19°58'0"N  
19°57'0"N

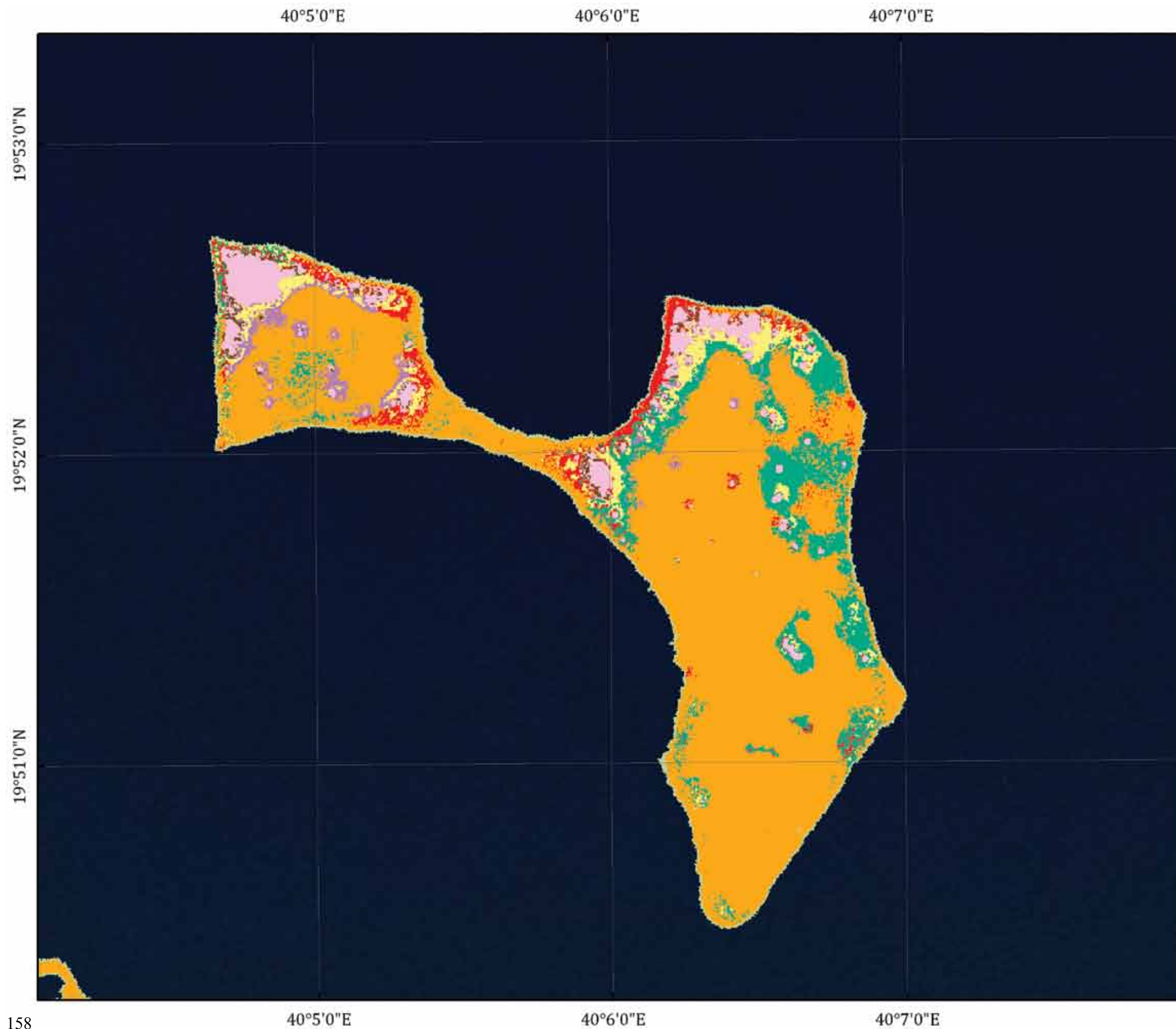


**Farasan Banks Habitats**

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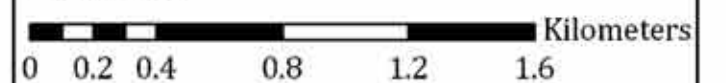


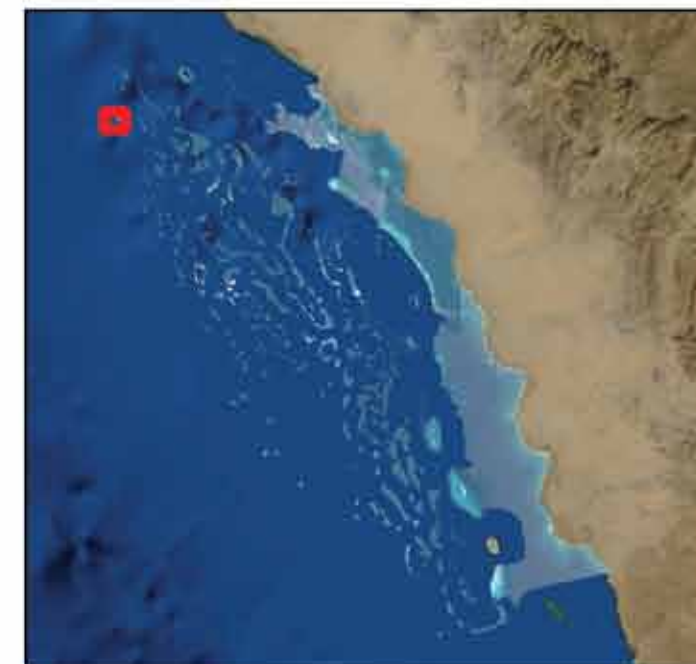
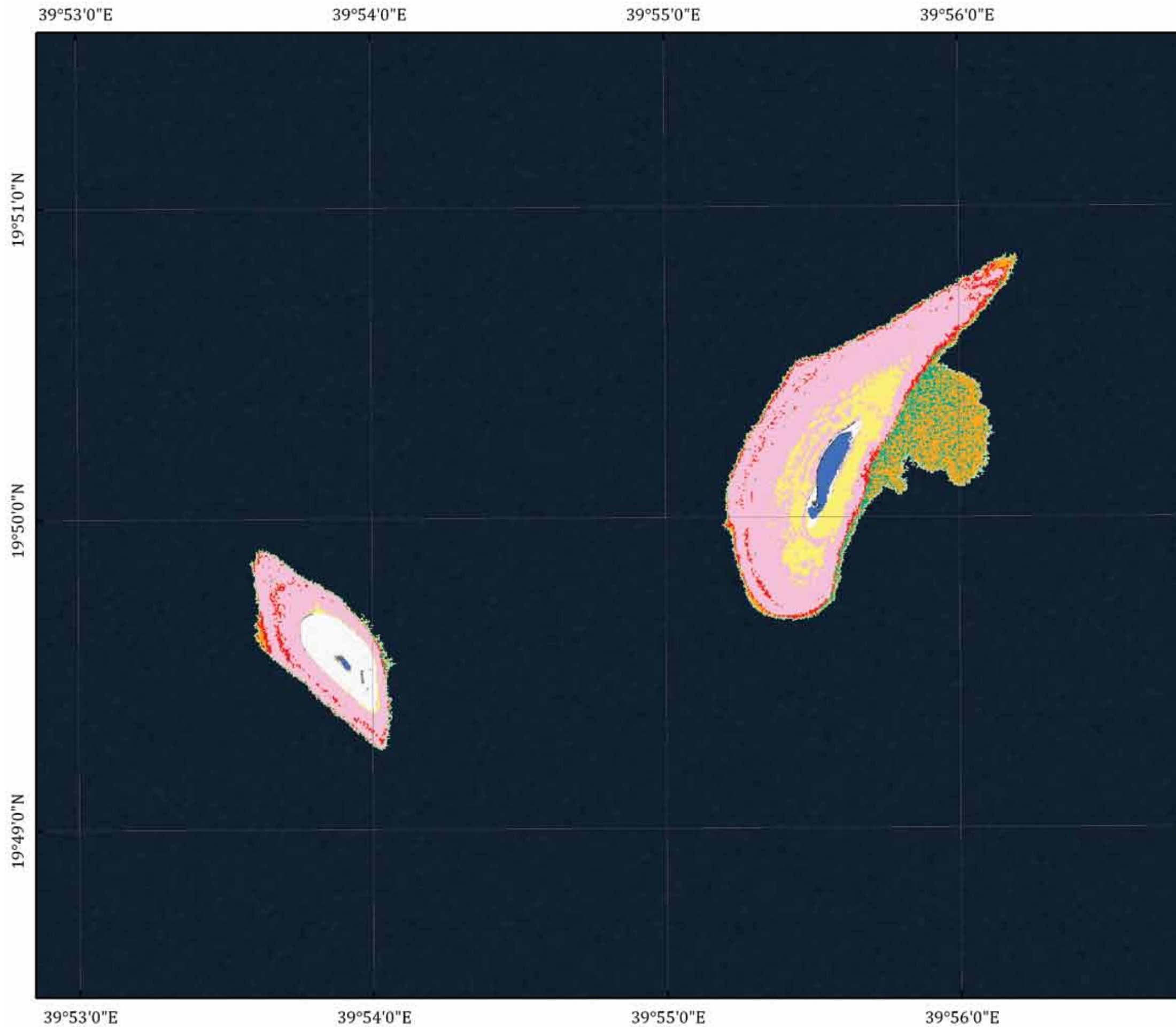


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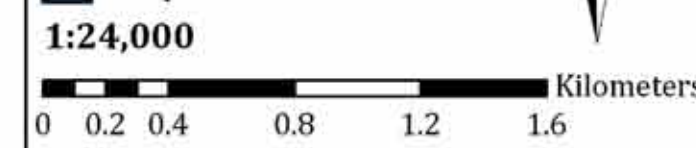
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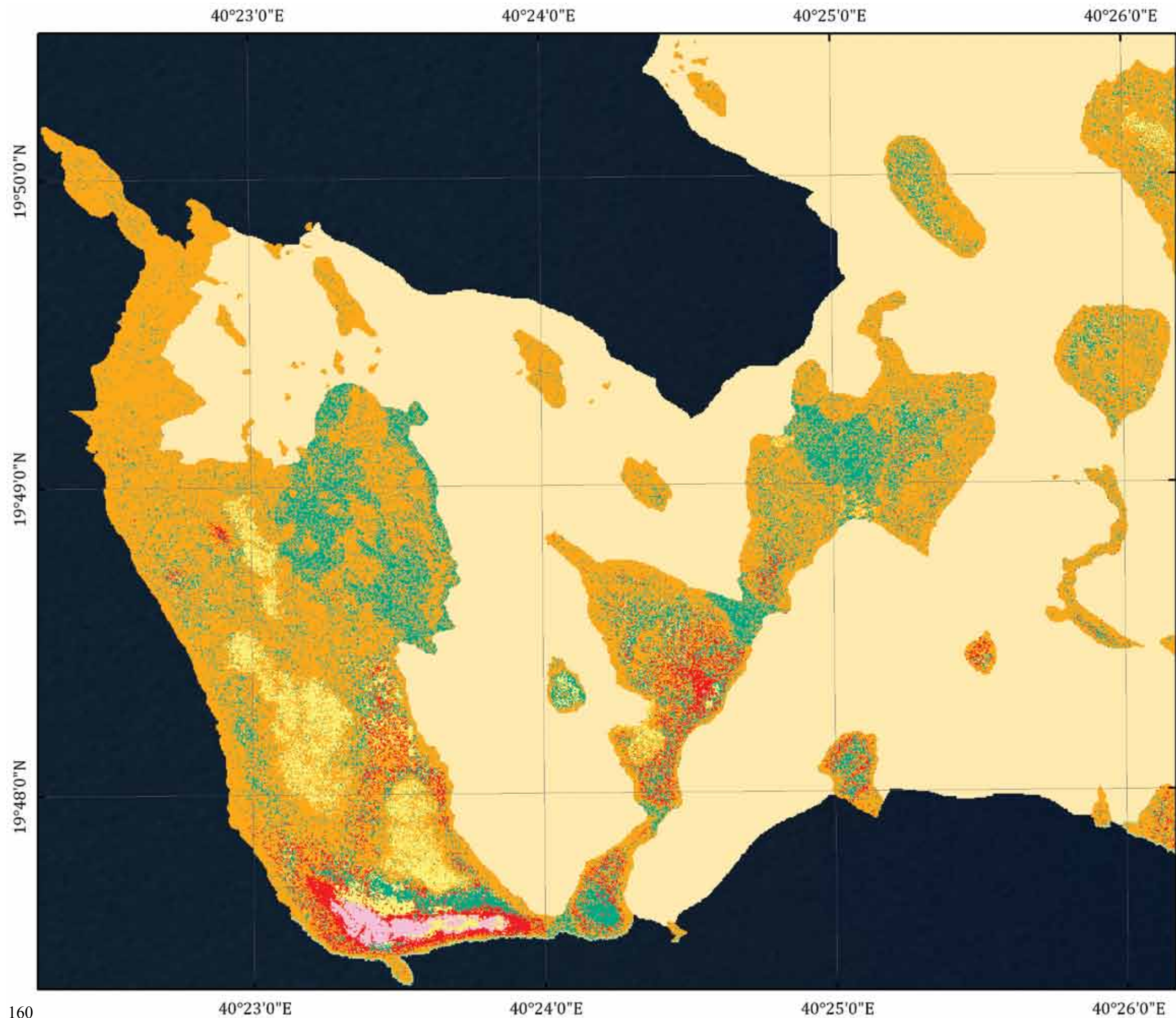


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- Sand and mud flats
- Deep water

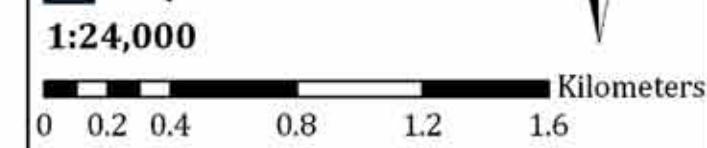


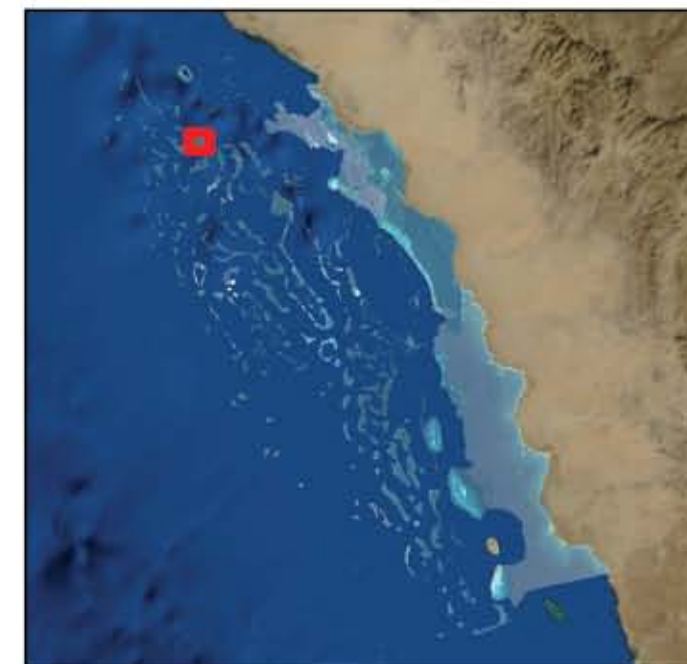
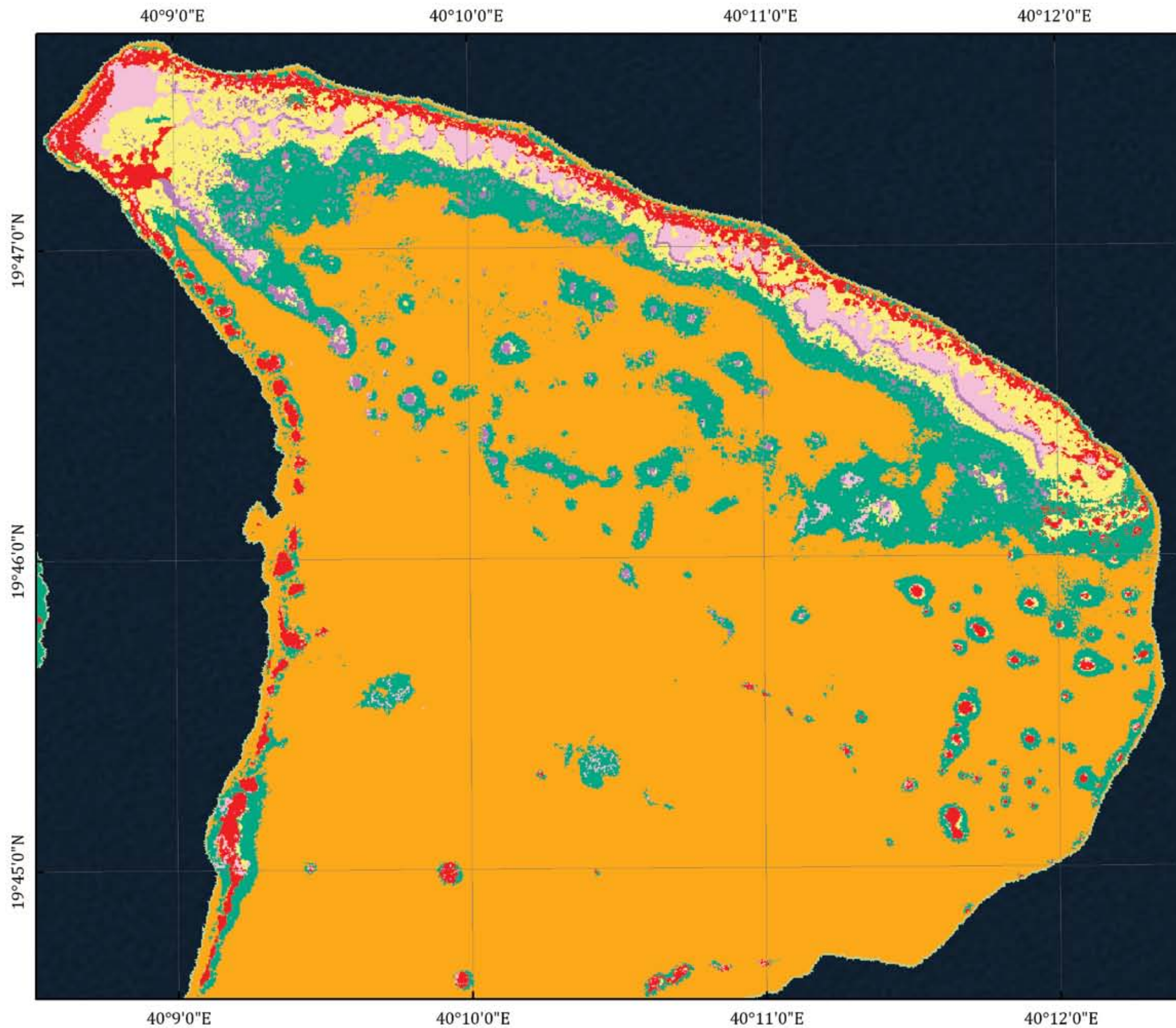




**Farasan Banks Habitats**

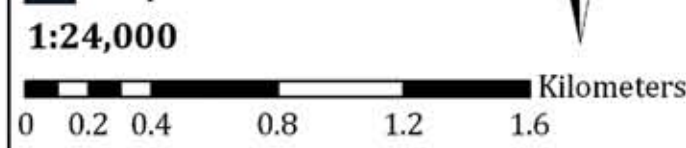
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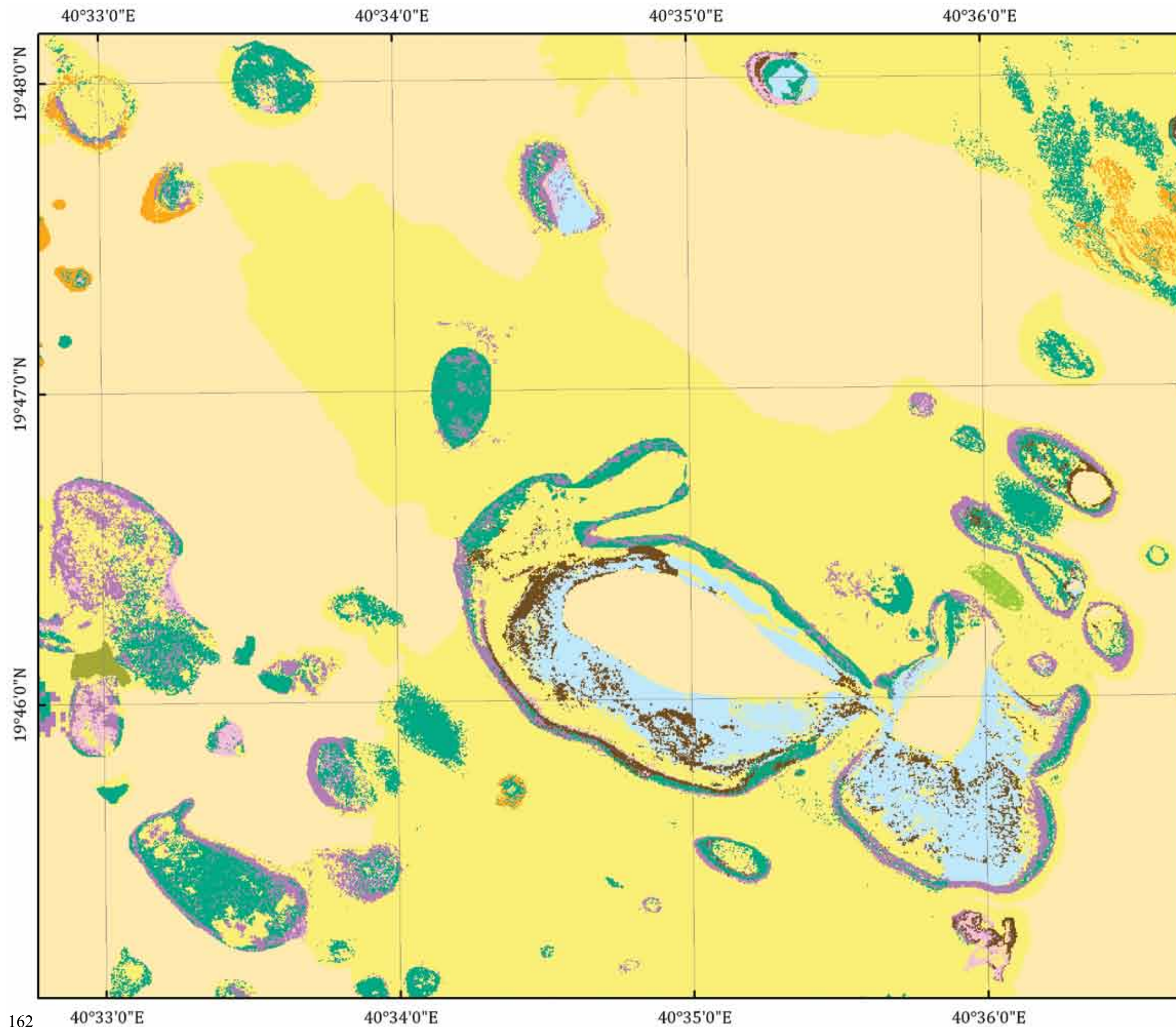




**Farasan Banks Habitats**

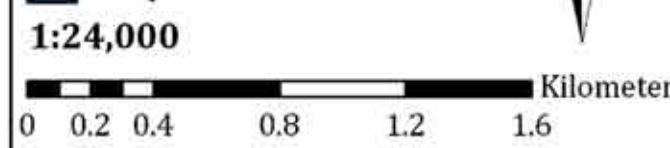
- Windward coral crests
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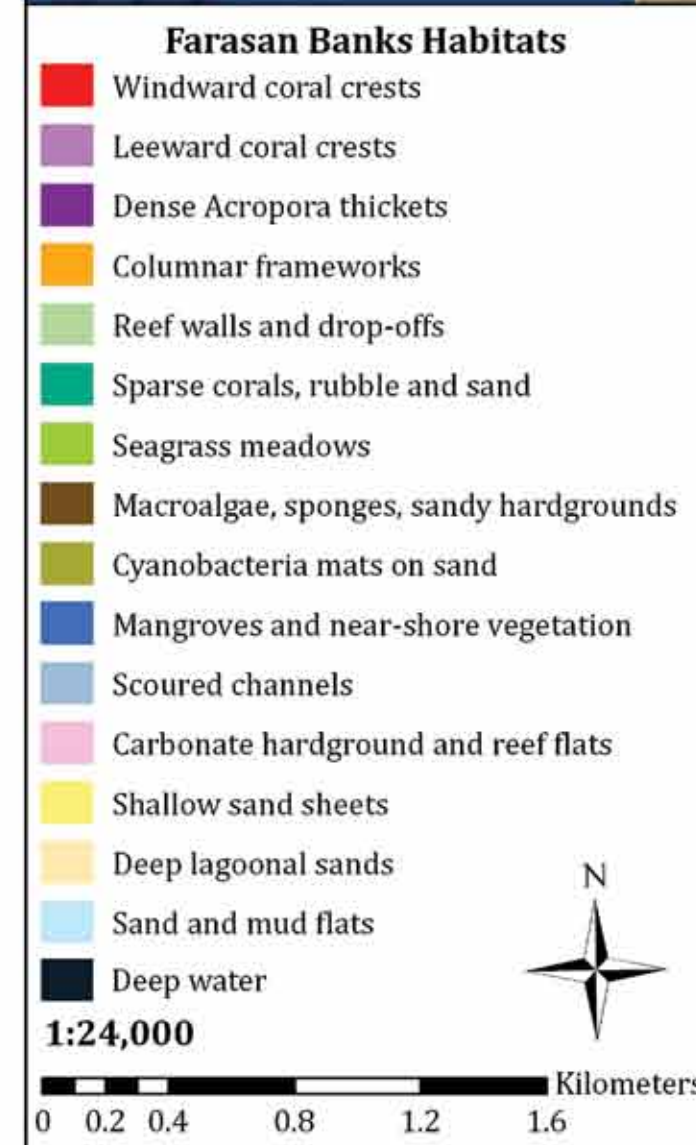
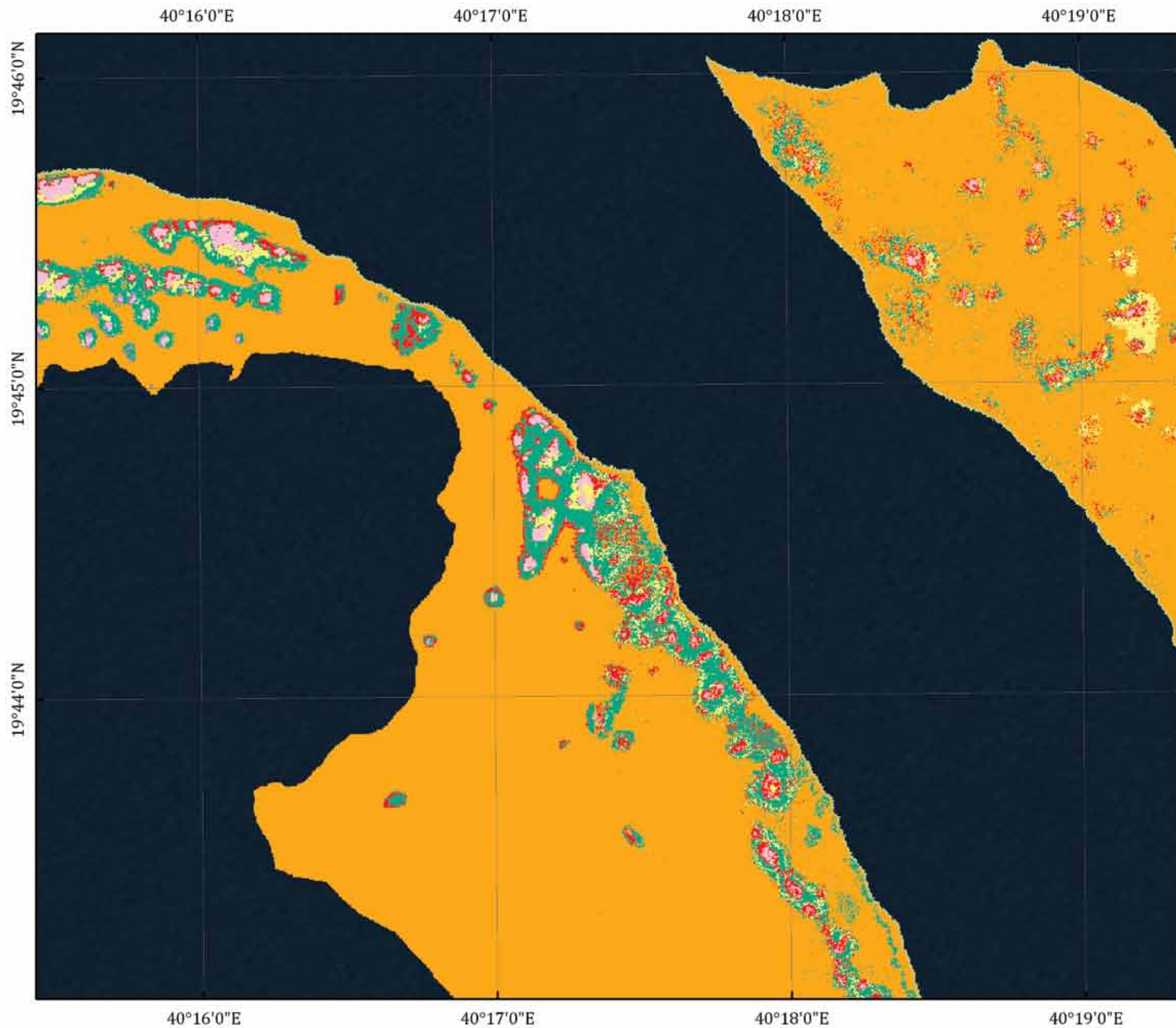


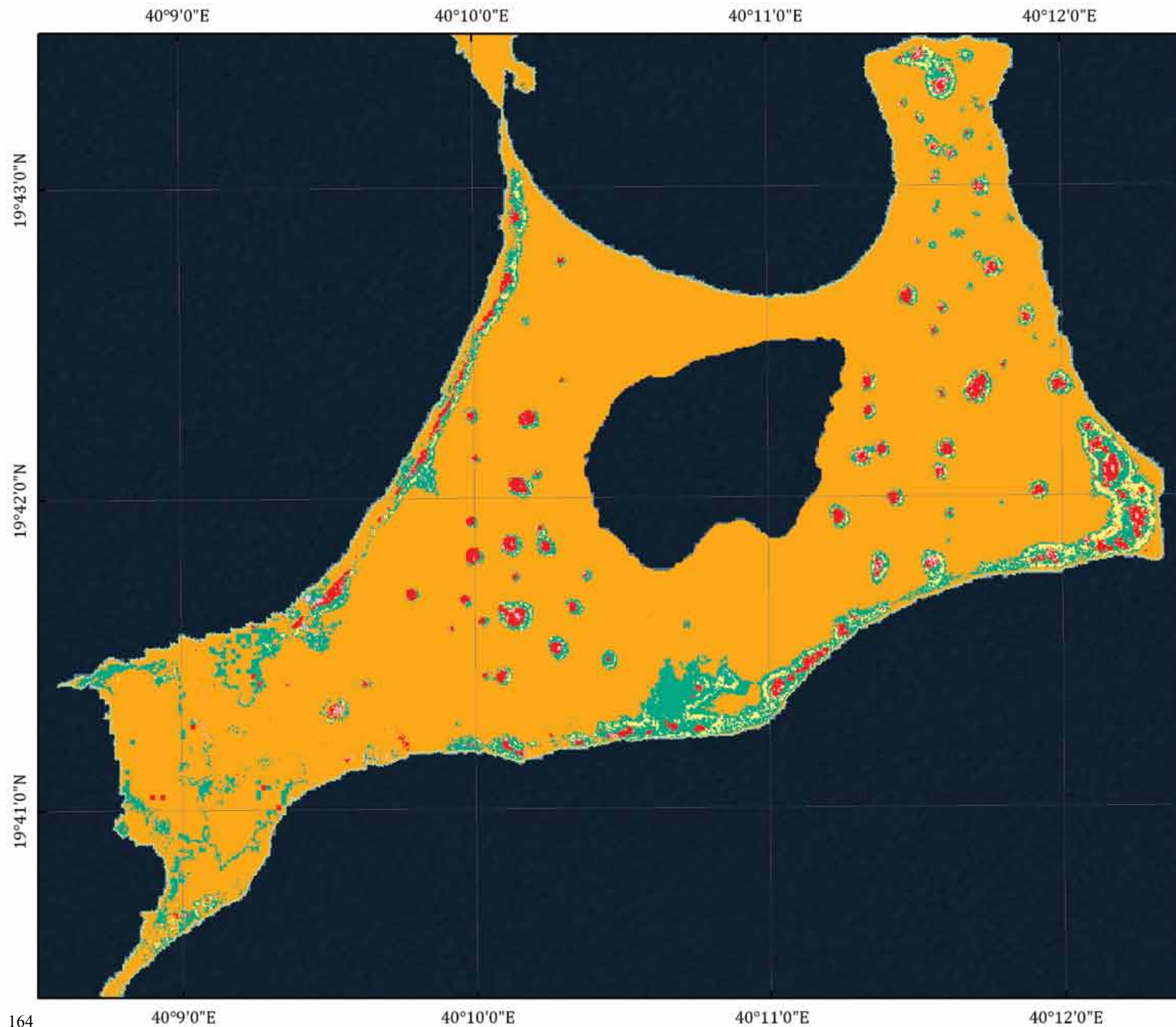


**Farasan Banks Habitats**

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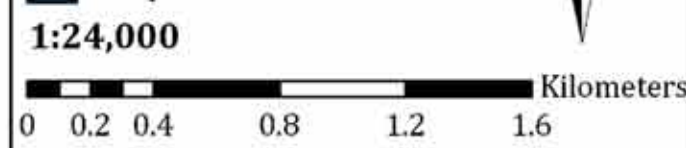


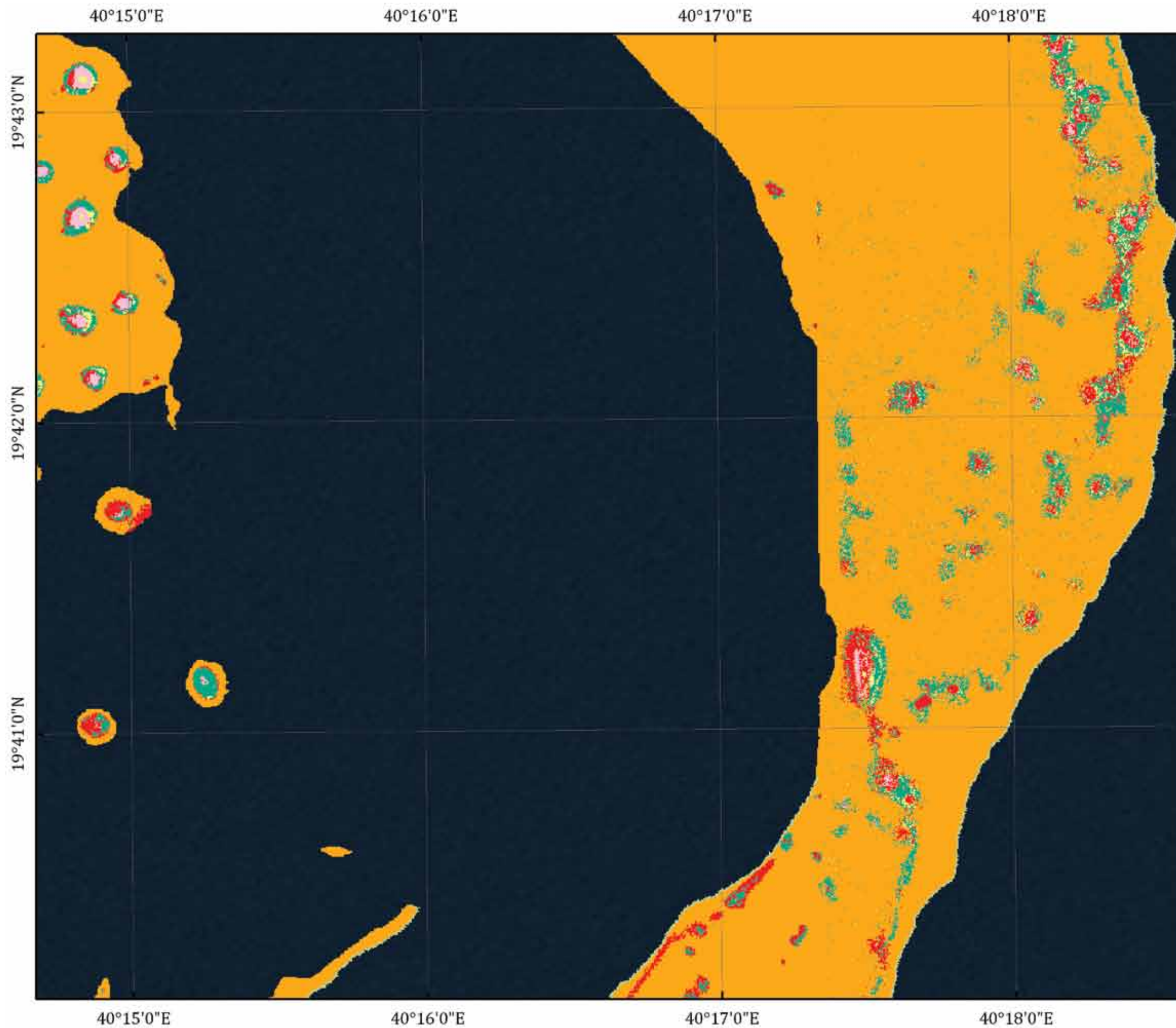




**Farasan Banks Habitats**

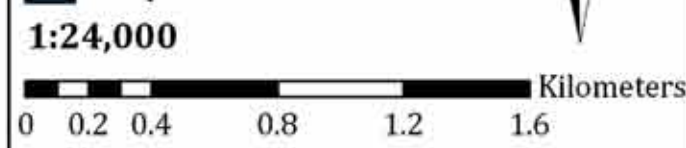
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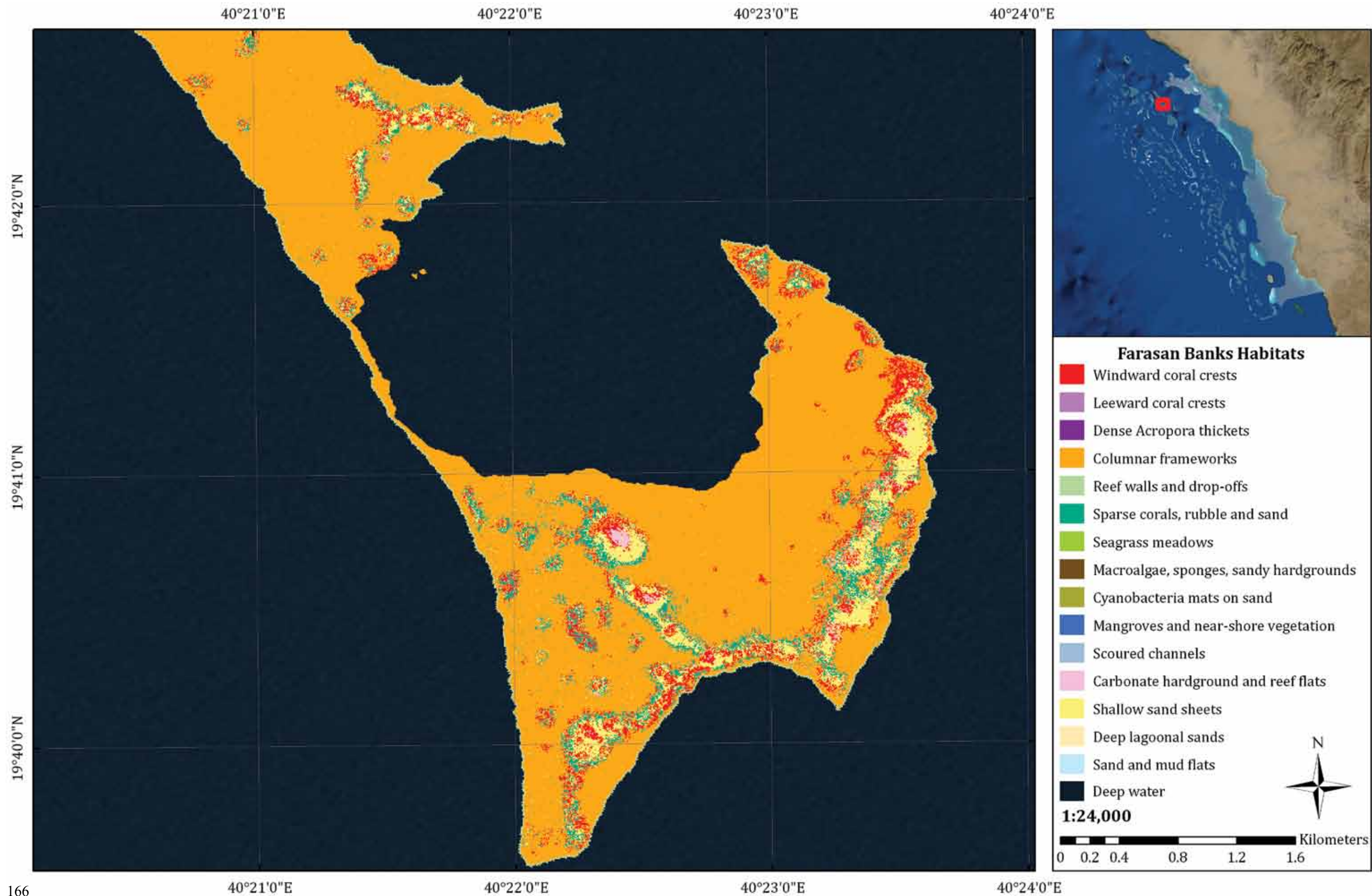


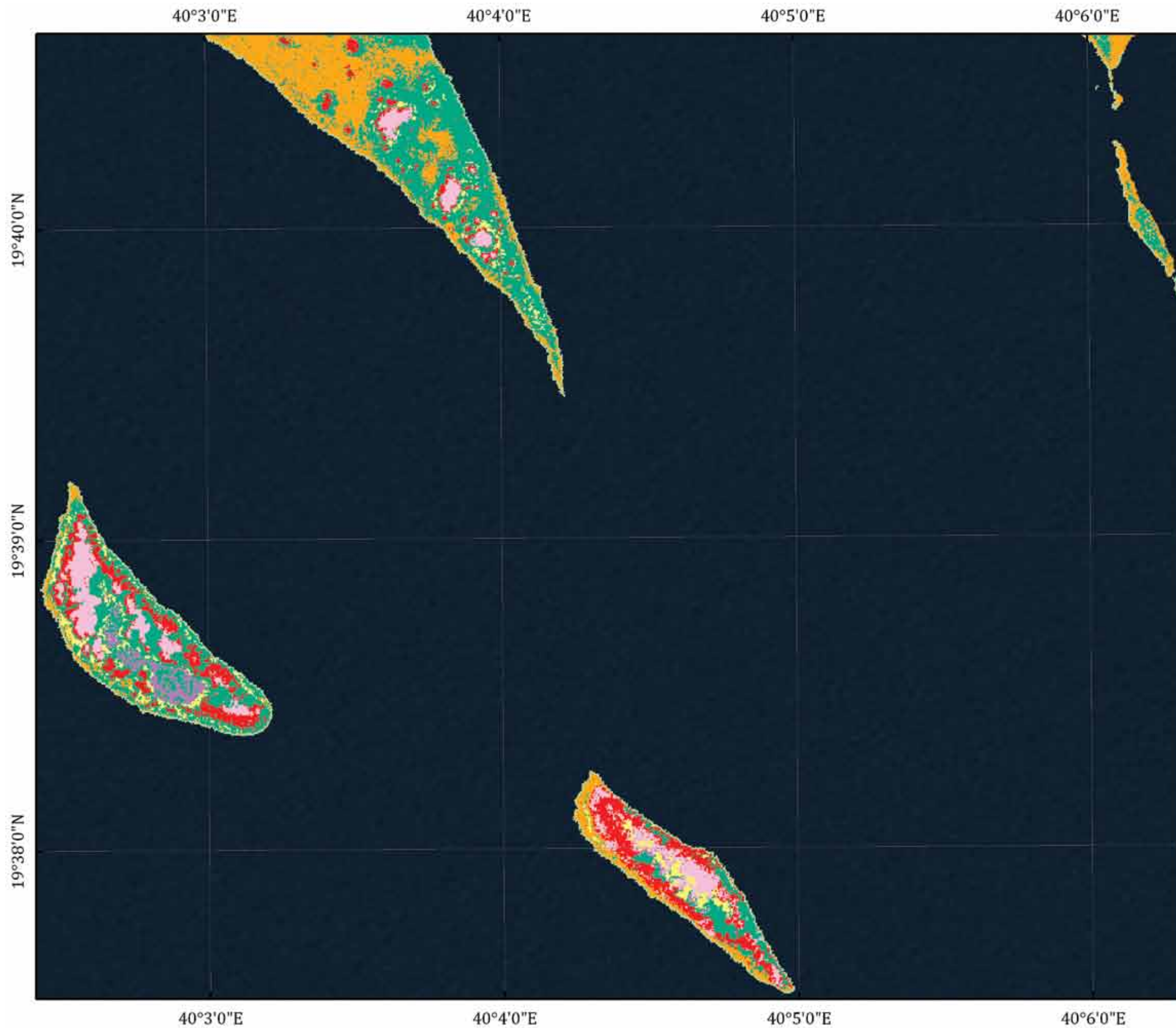


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**1:24,000**





40°26'0"E

40°27'0"E

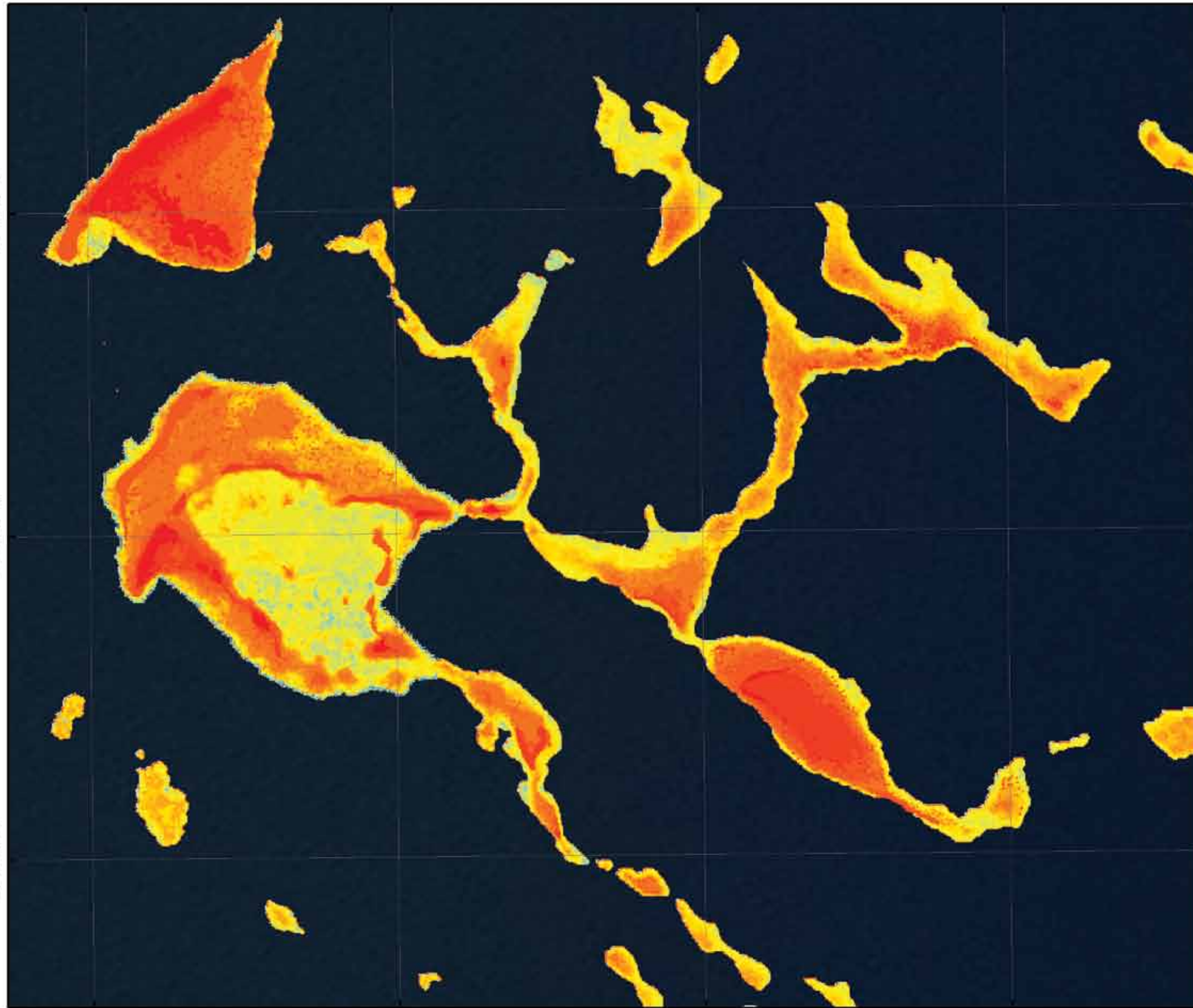
40°28'0"E

40°29'0"E

19°40'0"N

19°39'0"N

19°38'0"N

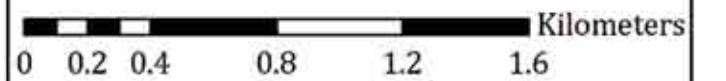


**Farasan Banks Bathymetry**

Depth, meters

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
4 - 4.9	18 - 18.9
5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

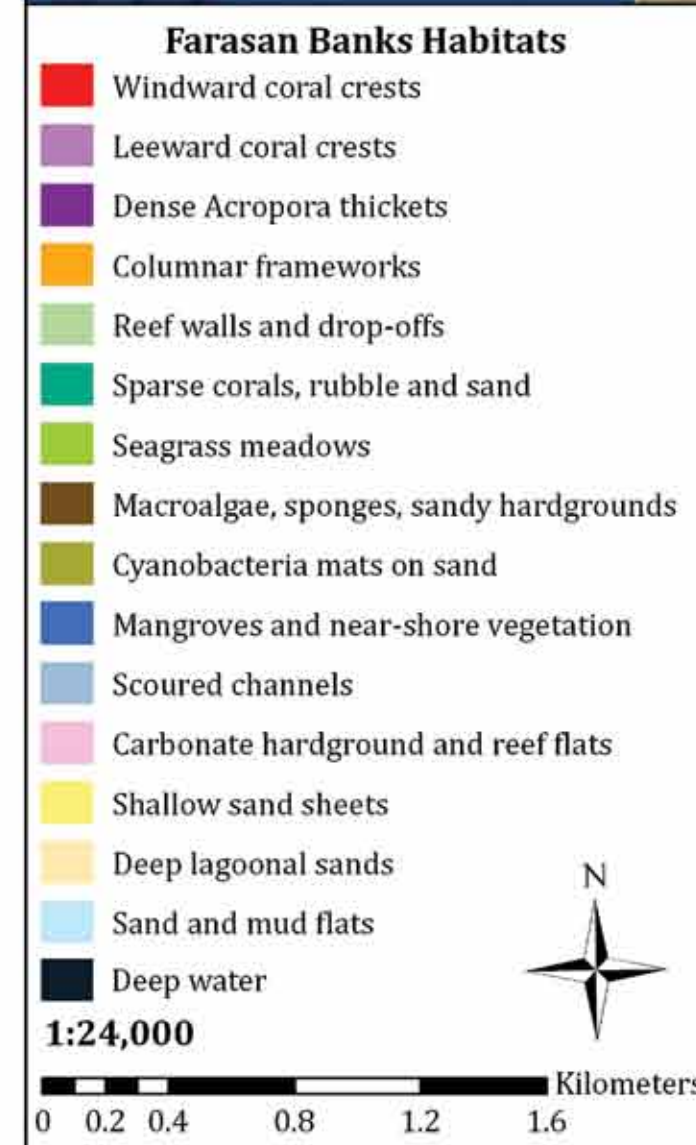
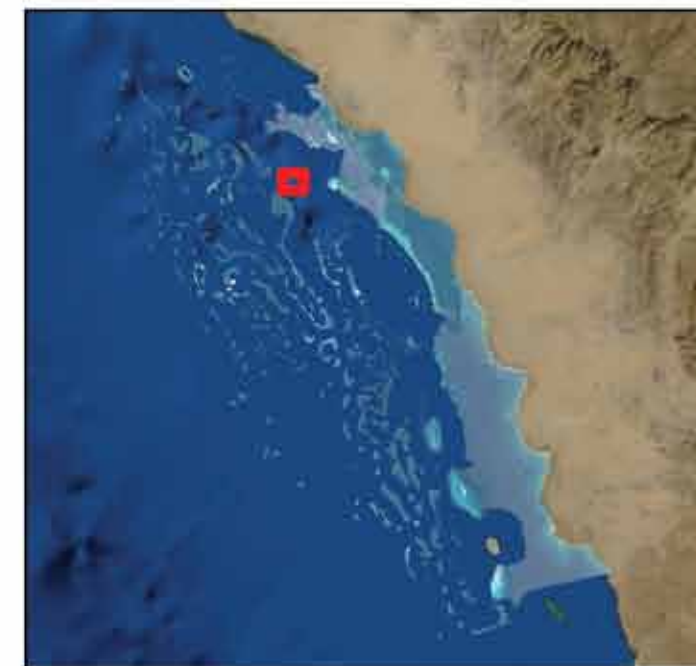
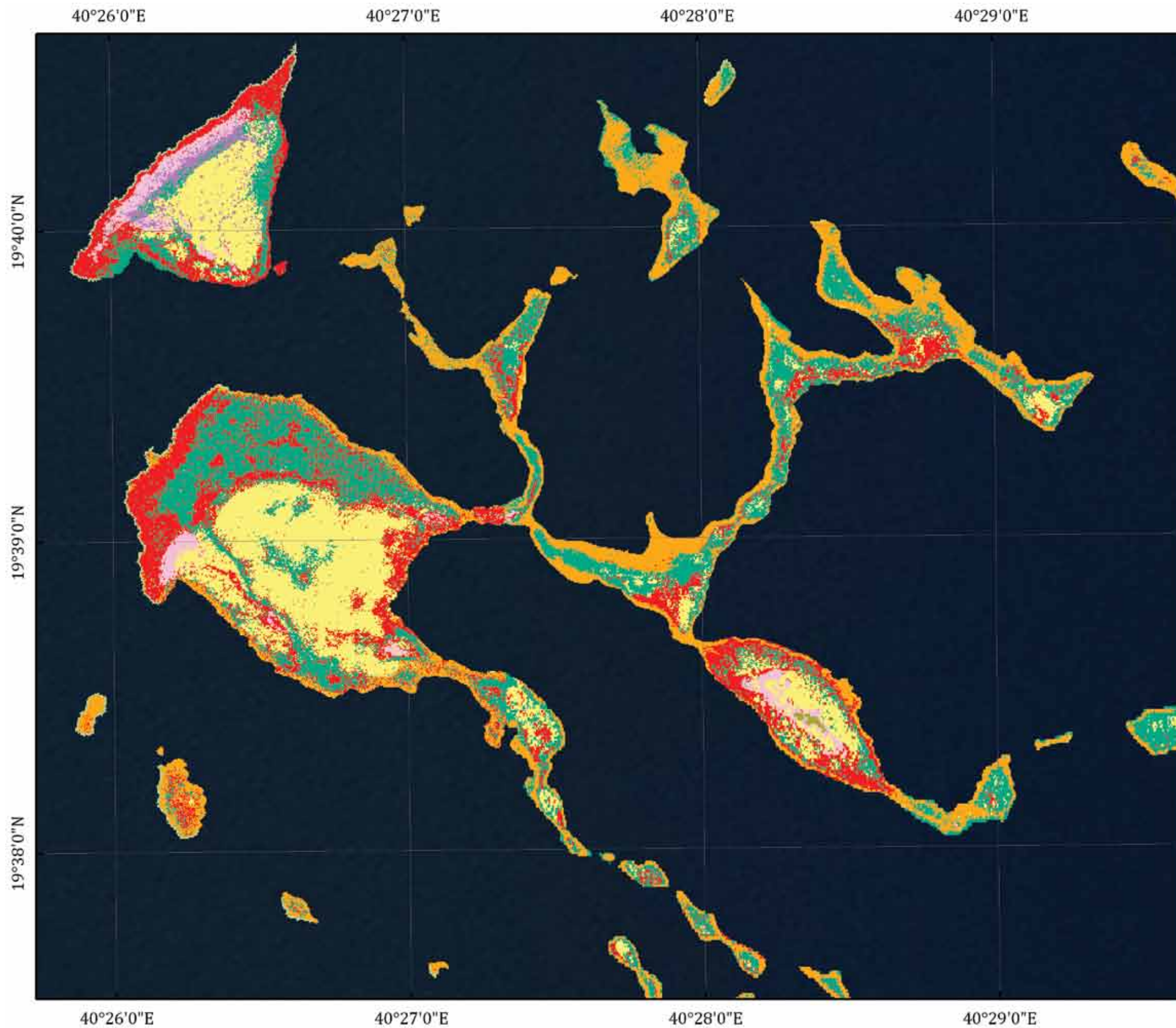
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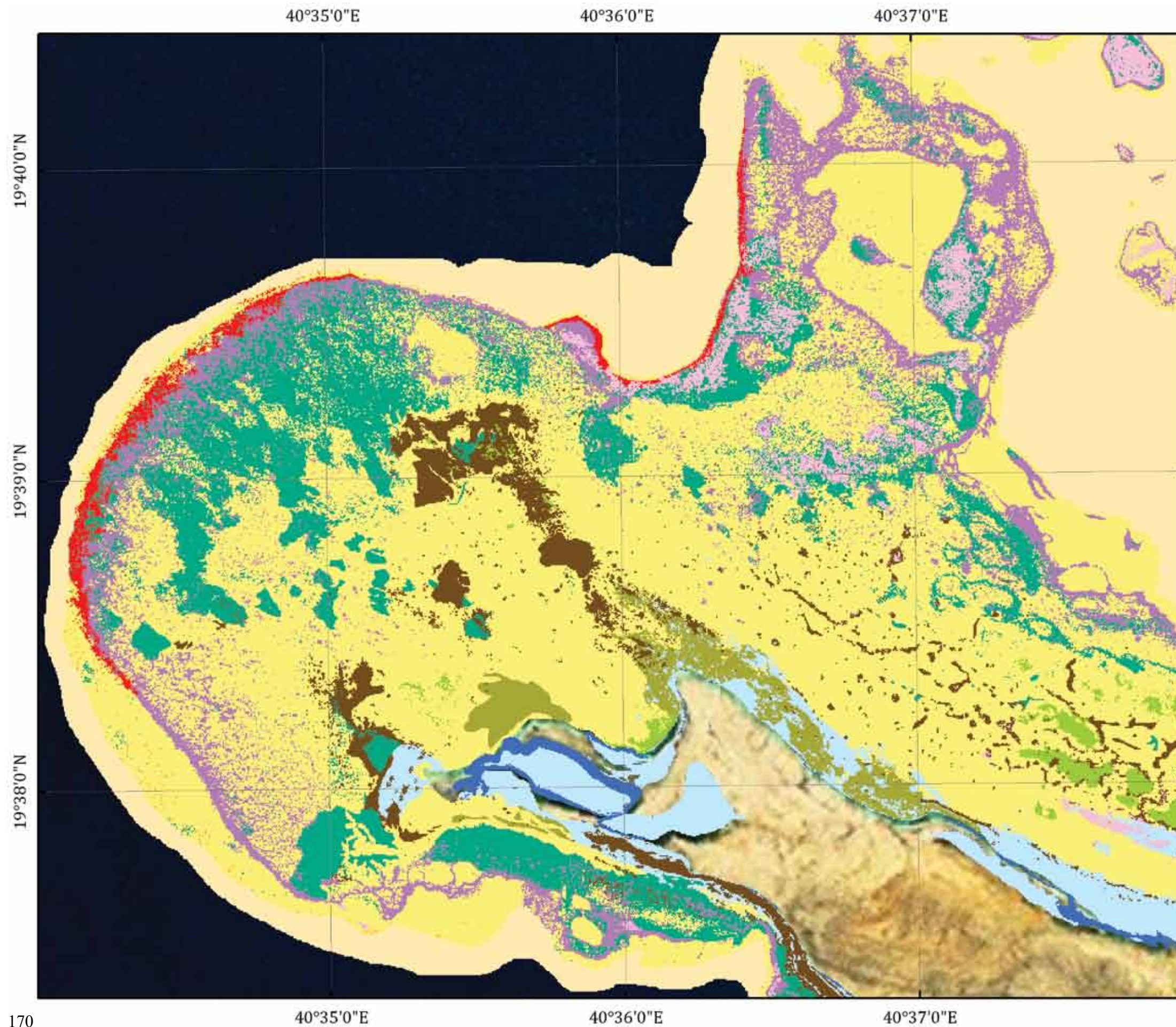


40°27'0"E

40°28'0"E

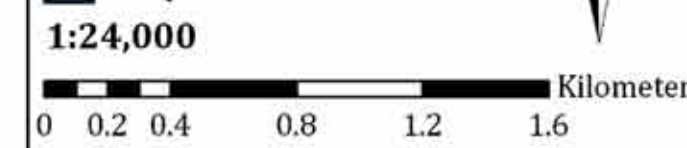
40°29'0"E

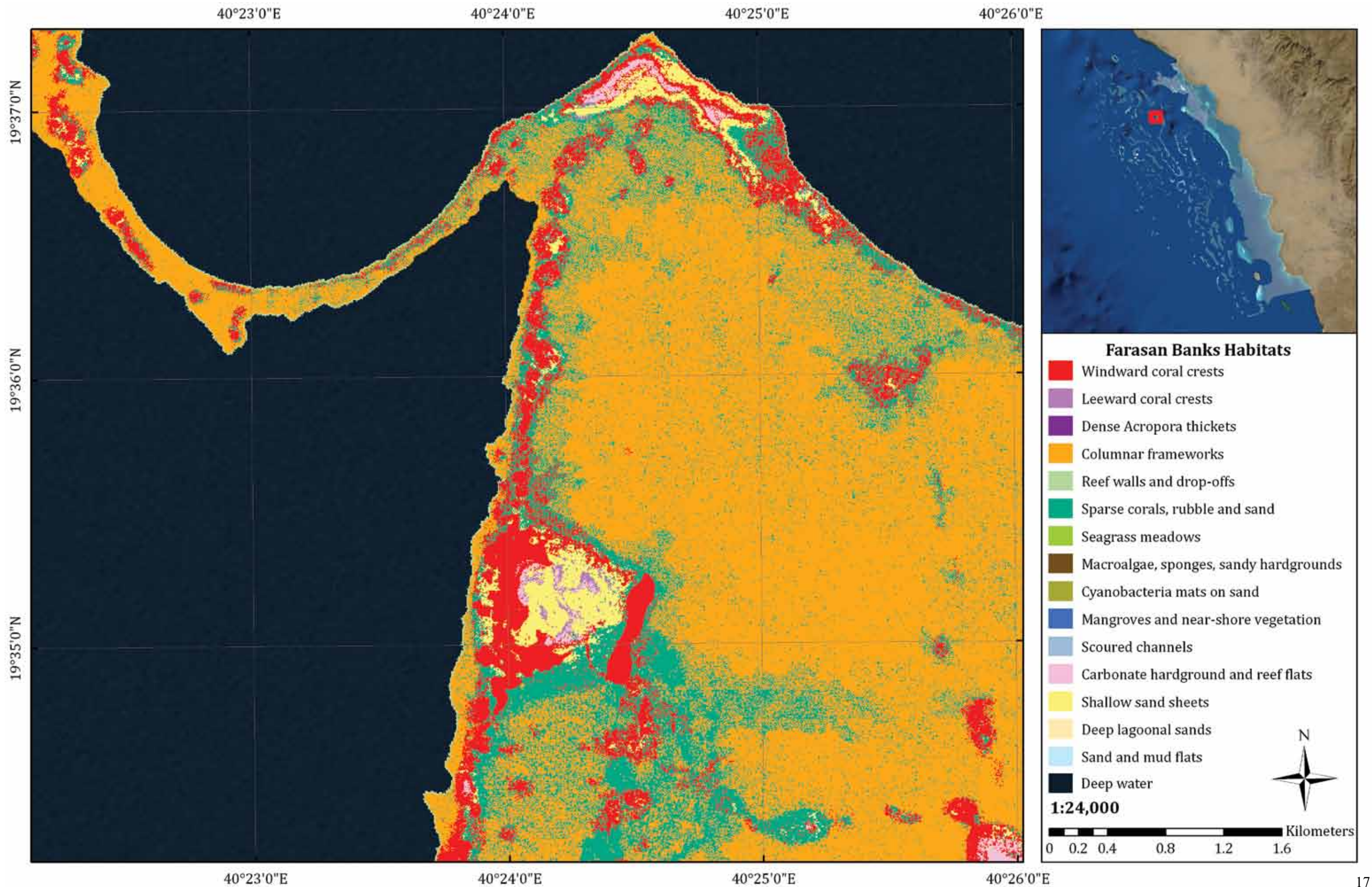


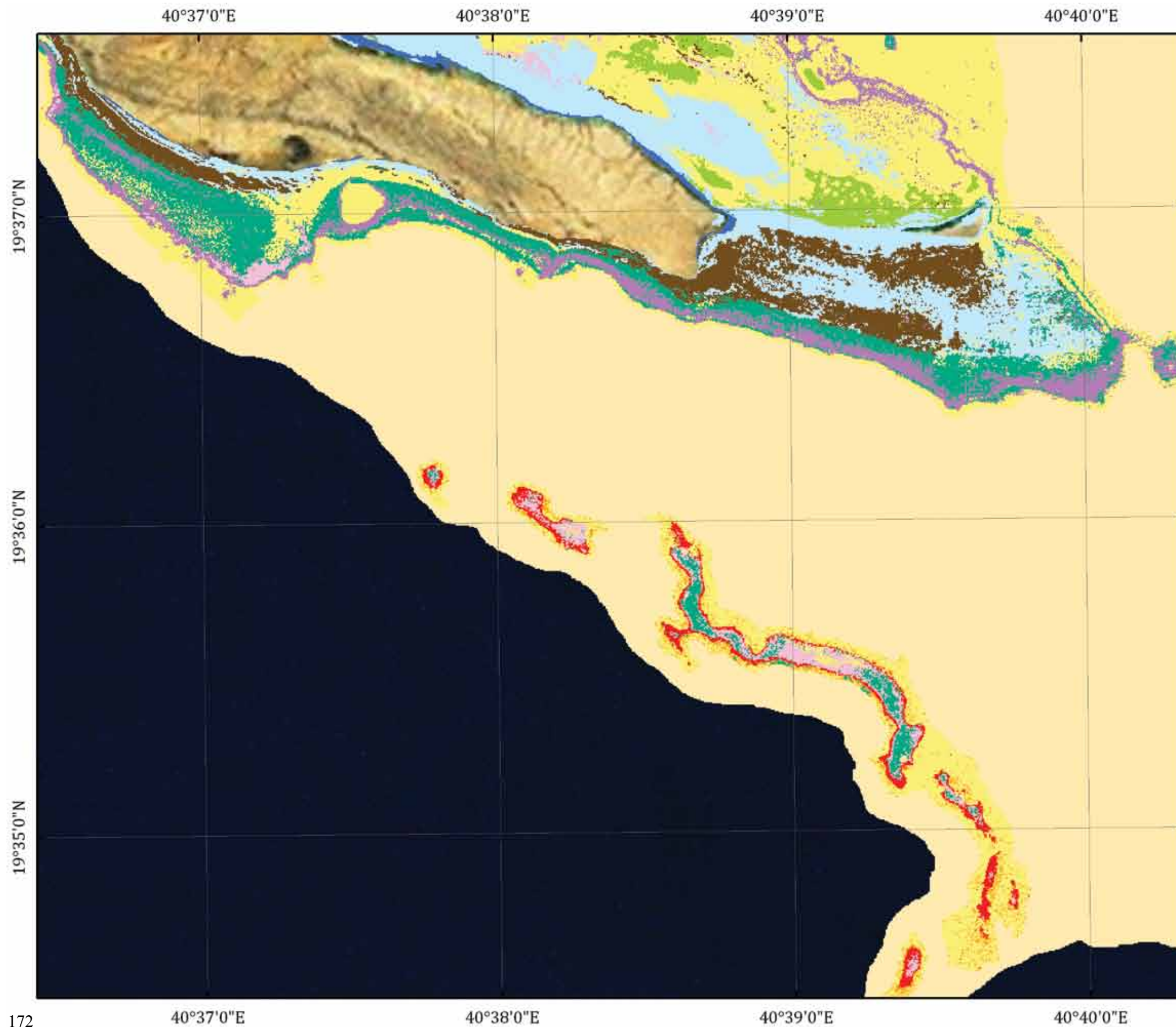


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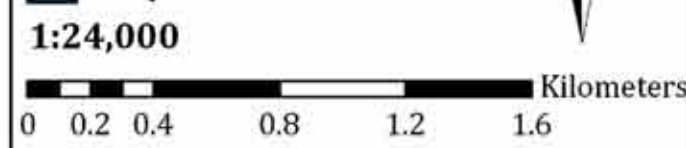


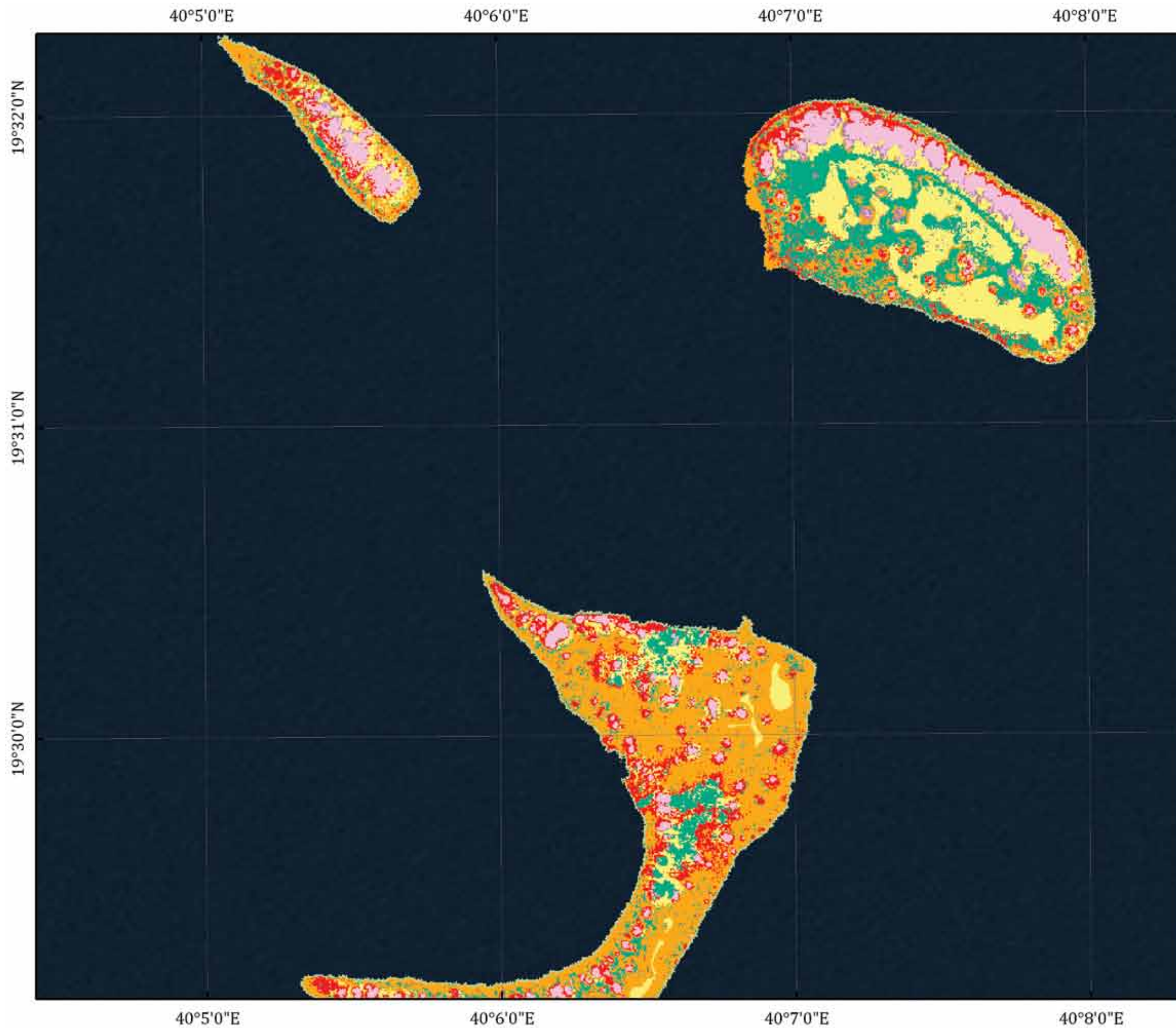




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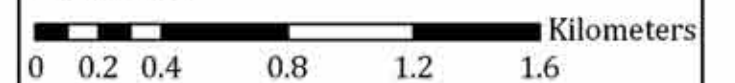




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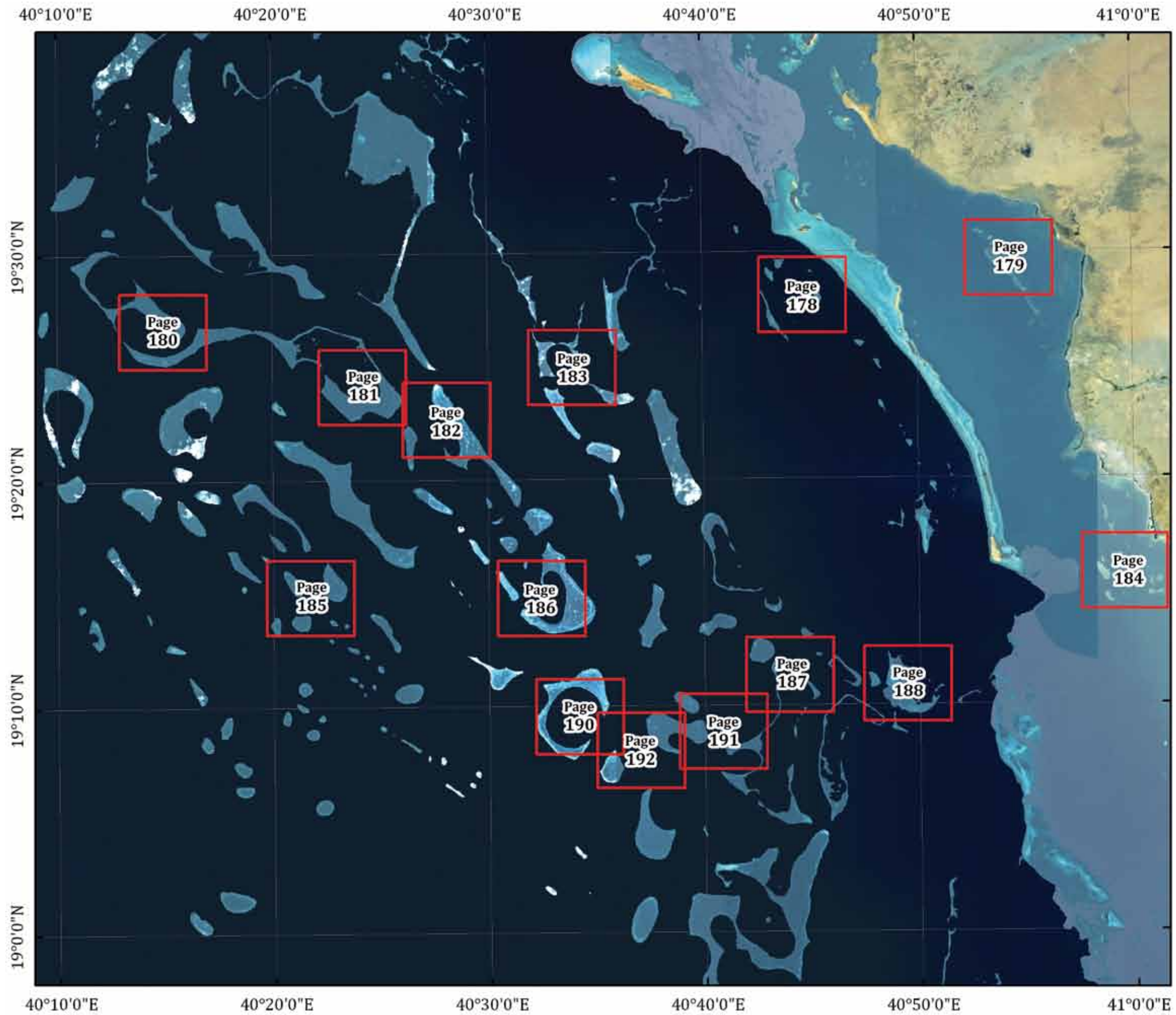




Dense stands of branching corals were found in protected environments on midshelf reefs at depths of 5-8 m. These reefs contained dozens of species of tabular, digitate, and branching colonies of *Acropora*, as well as small colonies of *Pocillopora*, *Stylophora*, and *Seriatopora* that are intermixed with small massive faviids, such as *Goniastrea*, *Favia*, *Favites*, and *Echinopora*. Live coral cover was very high, often exceeding 50-70%, with multiple canopy layers. However, on several *Acropora*-dominated reefs, corals exhibited extensive recent mortality associated with outbreaks of *Acanthaster planci*, commonly known as crown of thorns (COTS) seastars.



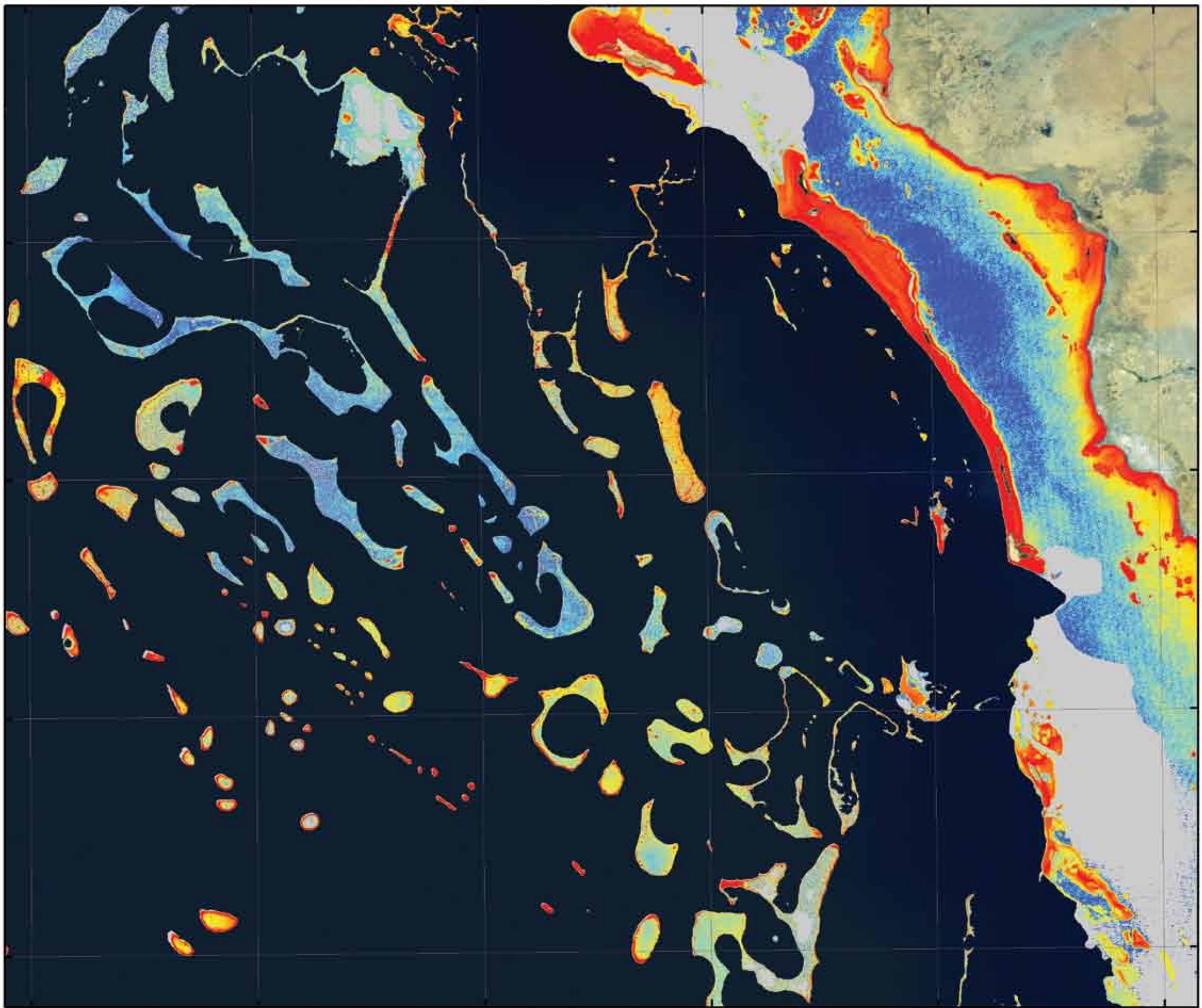
Closeup of a few branches of *Acropora* spp. The taxon is characterized by two distinct types of corallites (skeletal structures that house the polyps: axial and radial).





40°10'0"E 40°20'0"E 40°30'0"E 40°40'0"E 40°50'0"E 41°0'0"E

19°30'0"N  
19°20'0"N  
19°10'0"N  
19°0'0"N



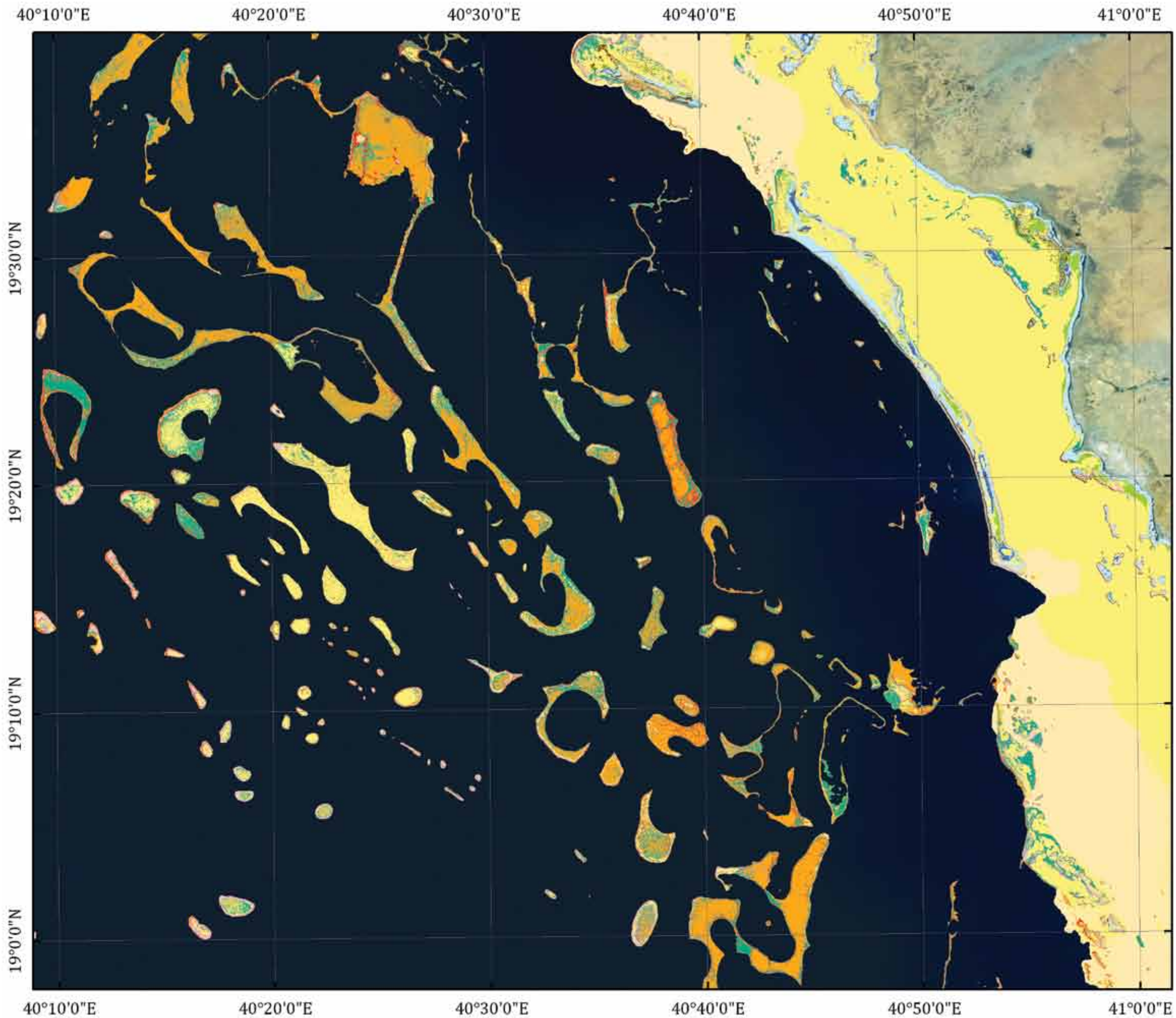
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Depth, meters

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8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	



176 40°20'0"E 40°30'0"E 40°40'0"E 40°50'0"E 41°0'0"E

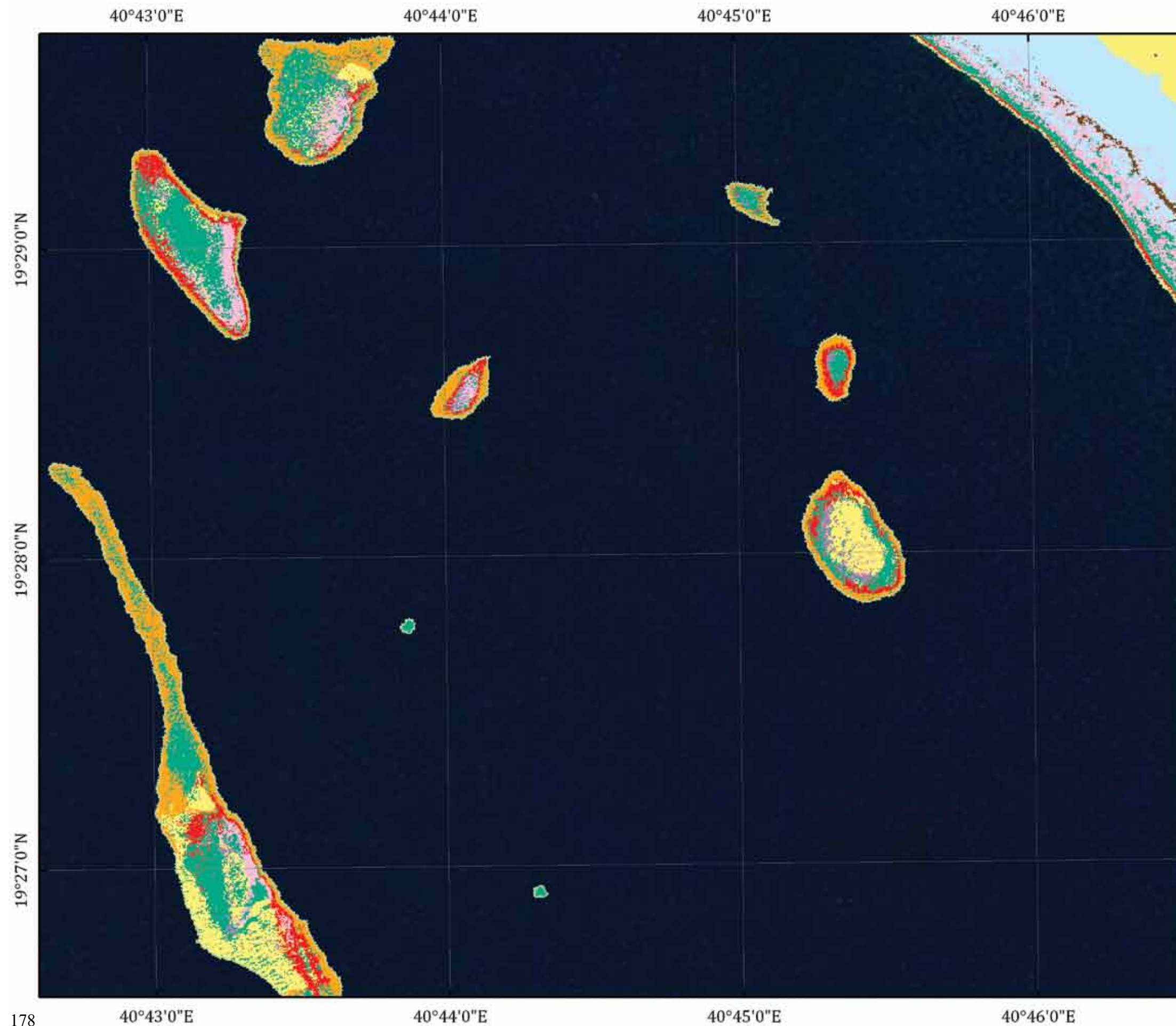


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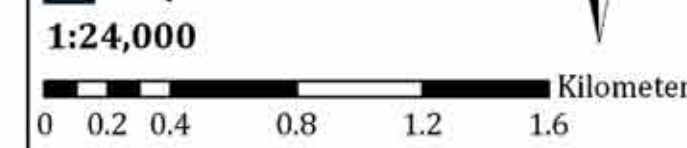
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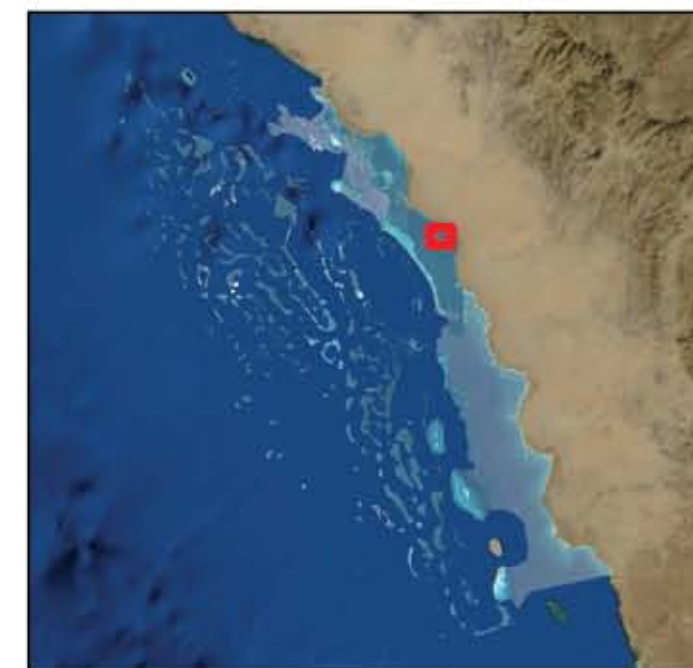
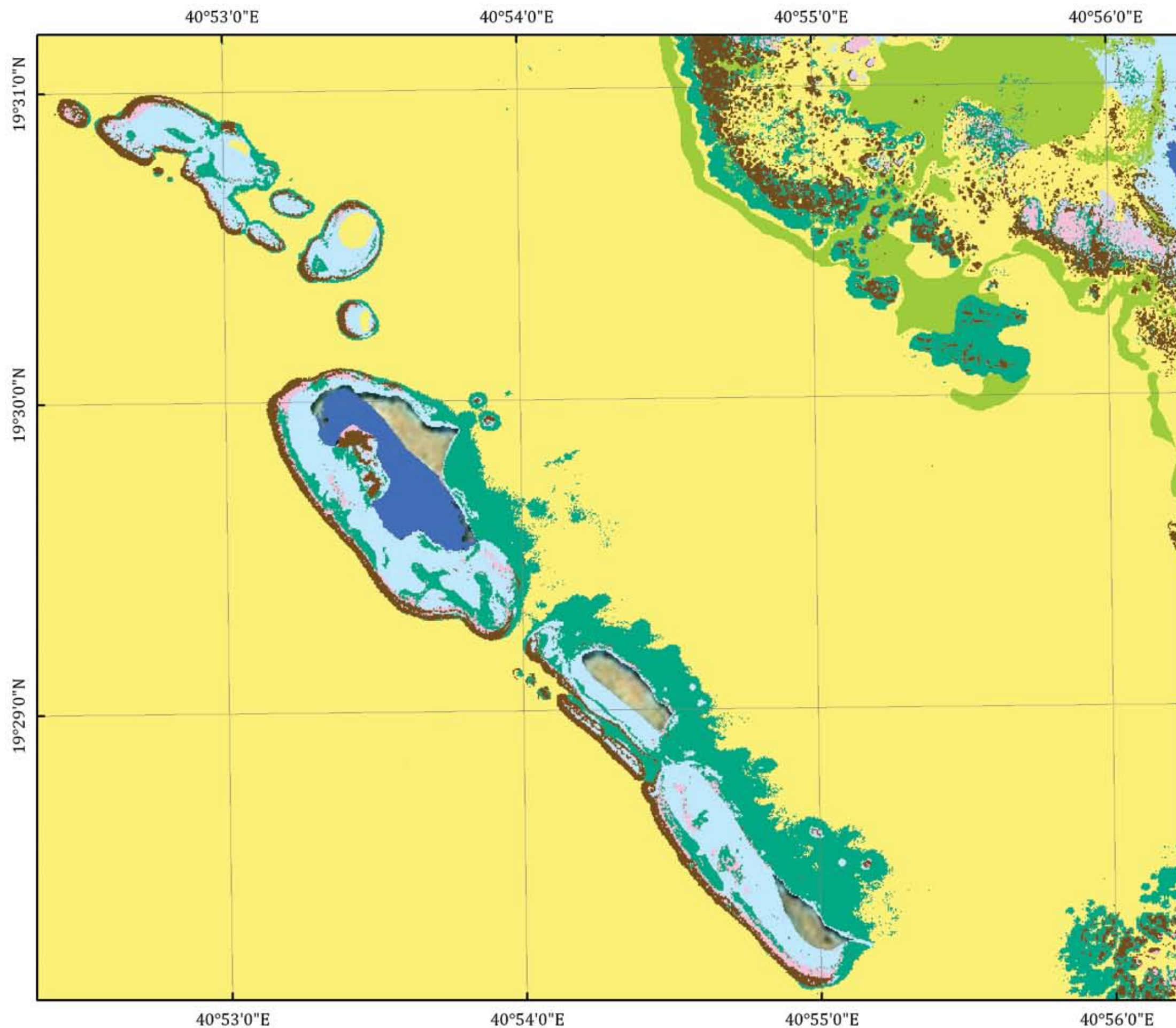
N  
  
 Kilometers  
 0 2.5 5 10 15 20



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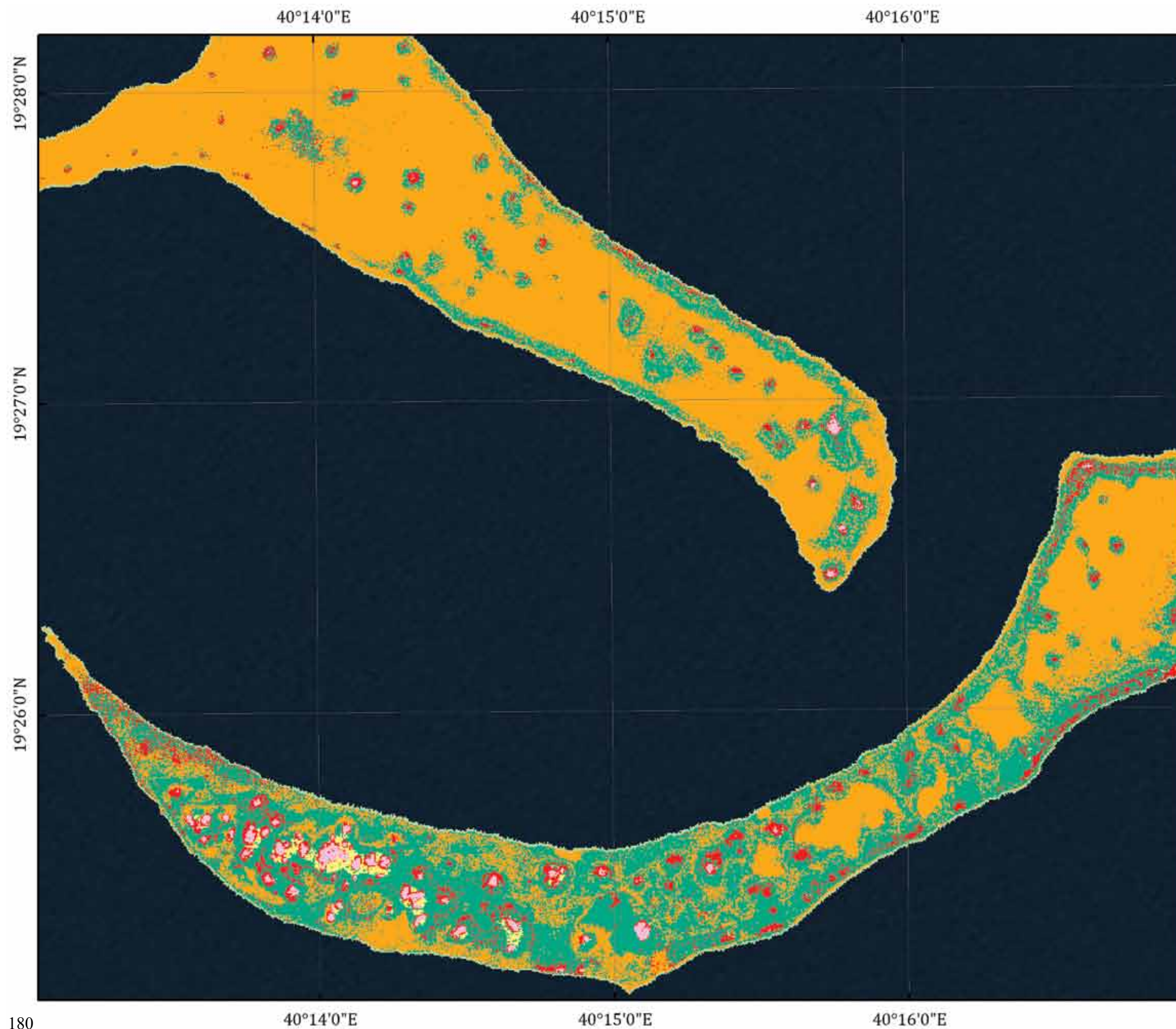


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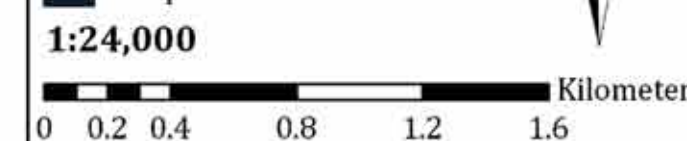
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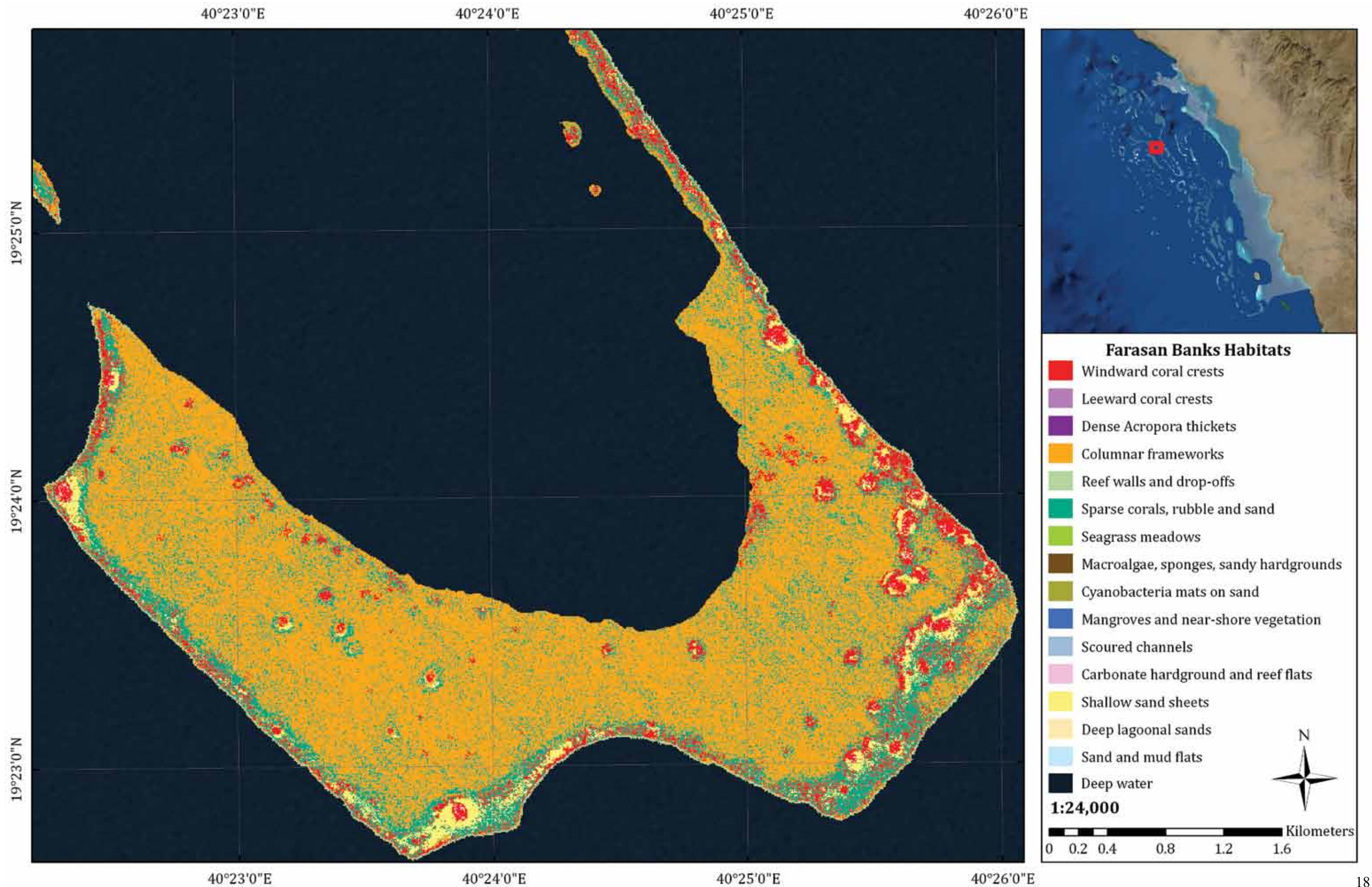


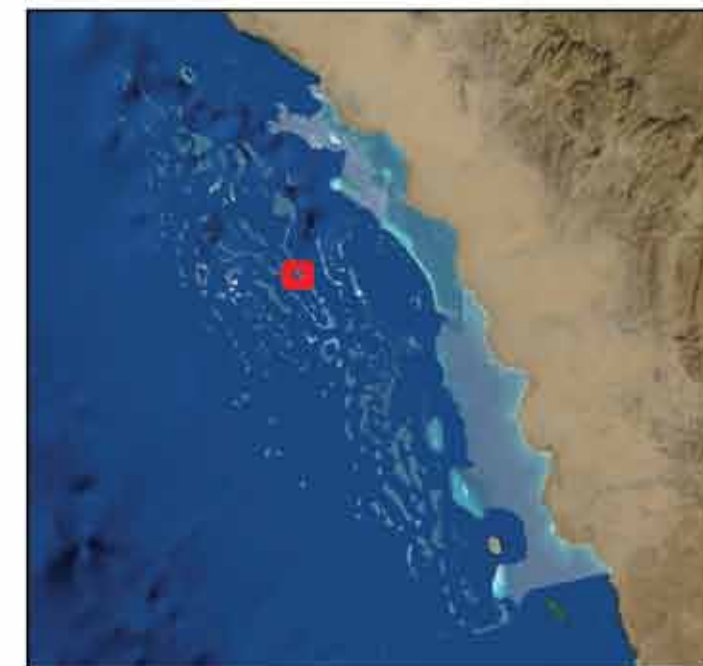
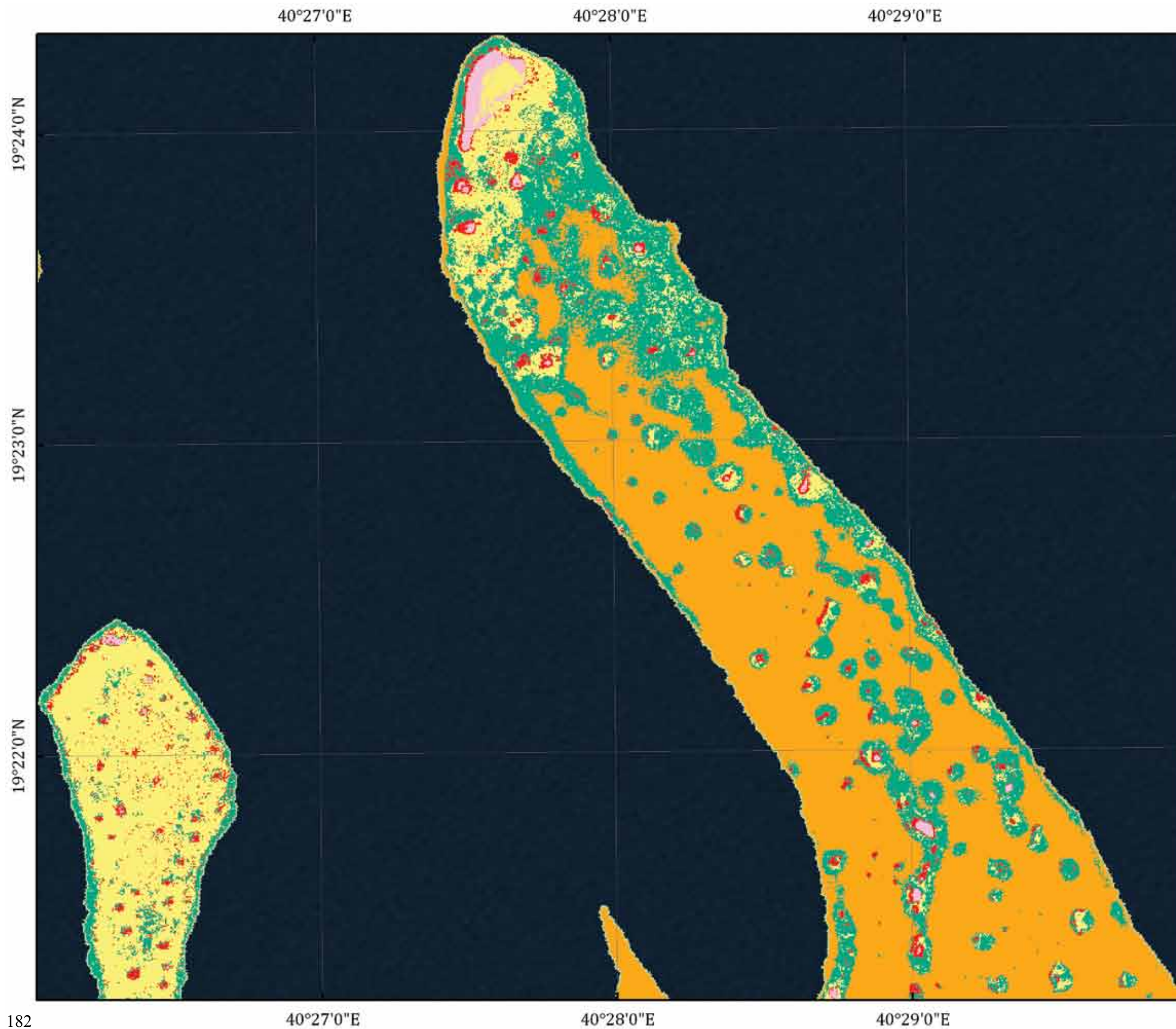


**Farasan Banks Habitats**

- Windward coral crests
- Leeward coral crests
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- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
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- Mangroves and near-shore vegetation
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water






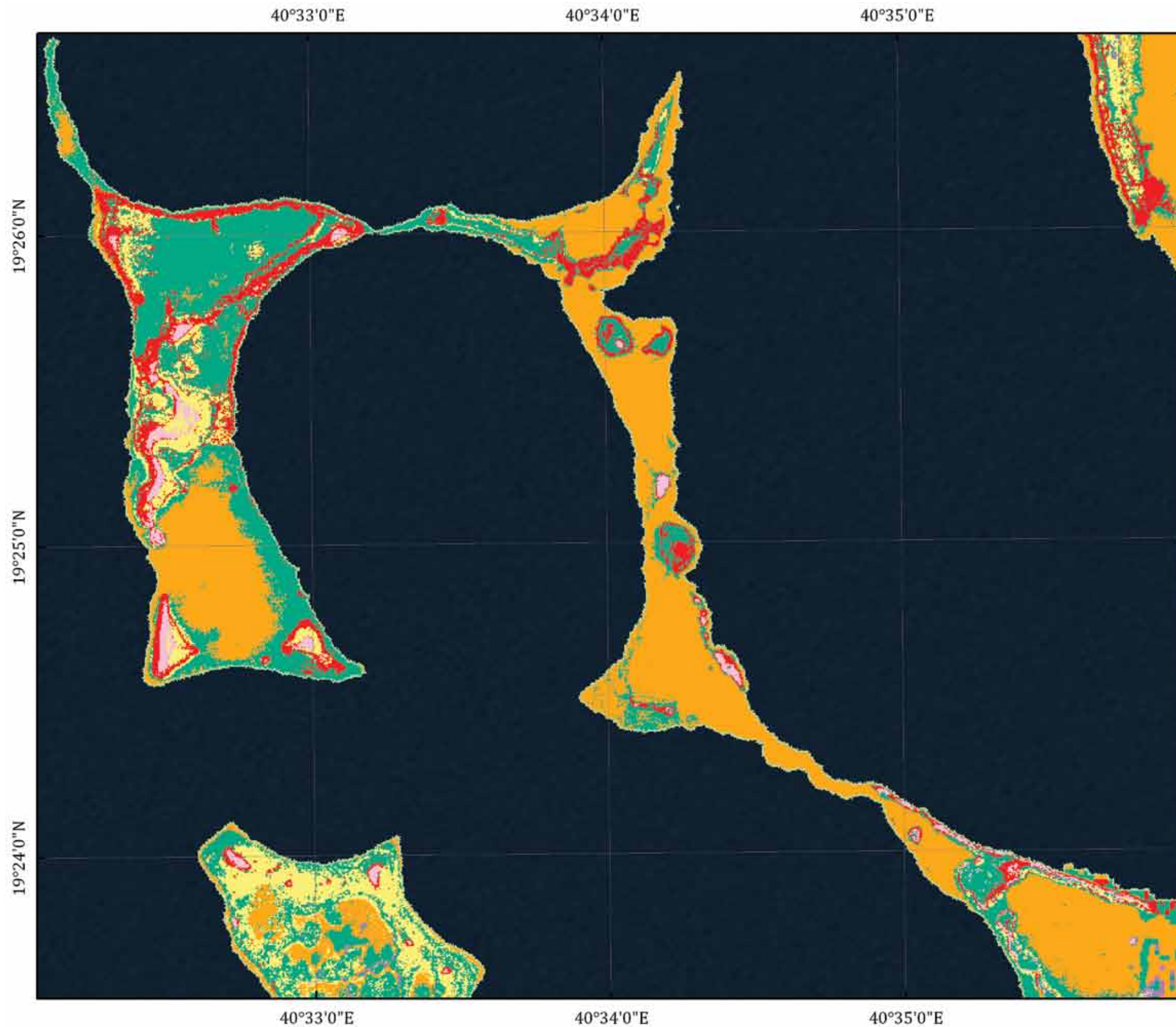


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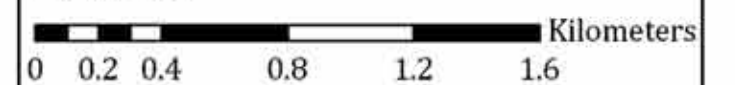
N  
  
 Kilometers  
 0 0.2 0.4 0.8 1.2 1.6



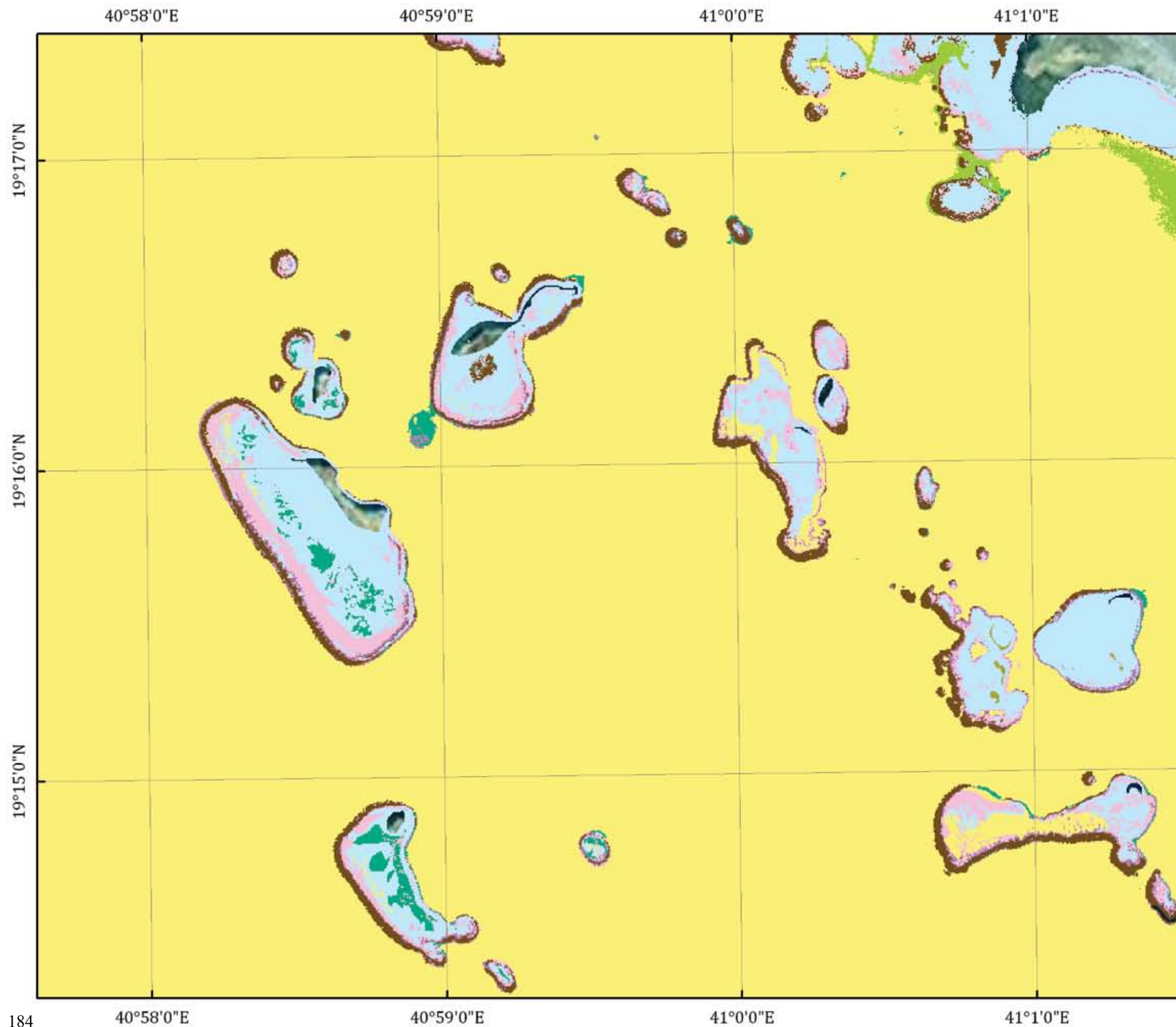
**Farasan Banks Habitats**

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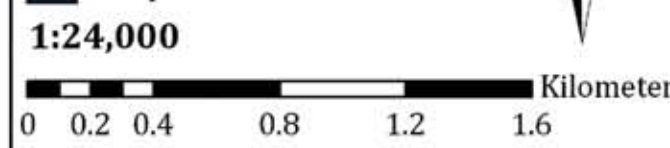


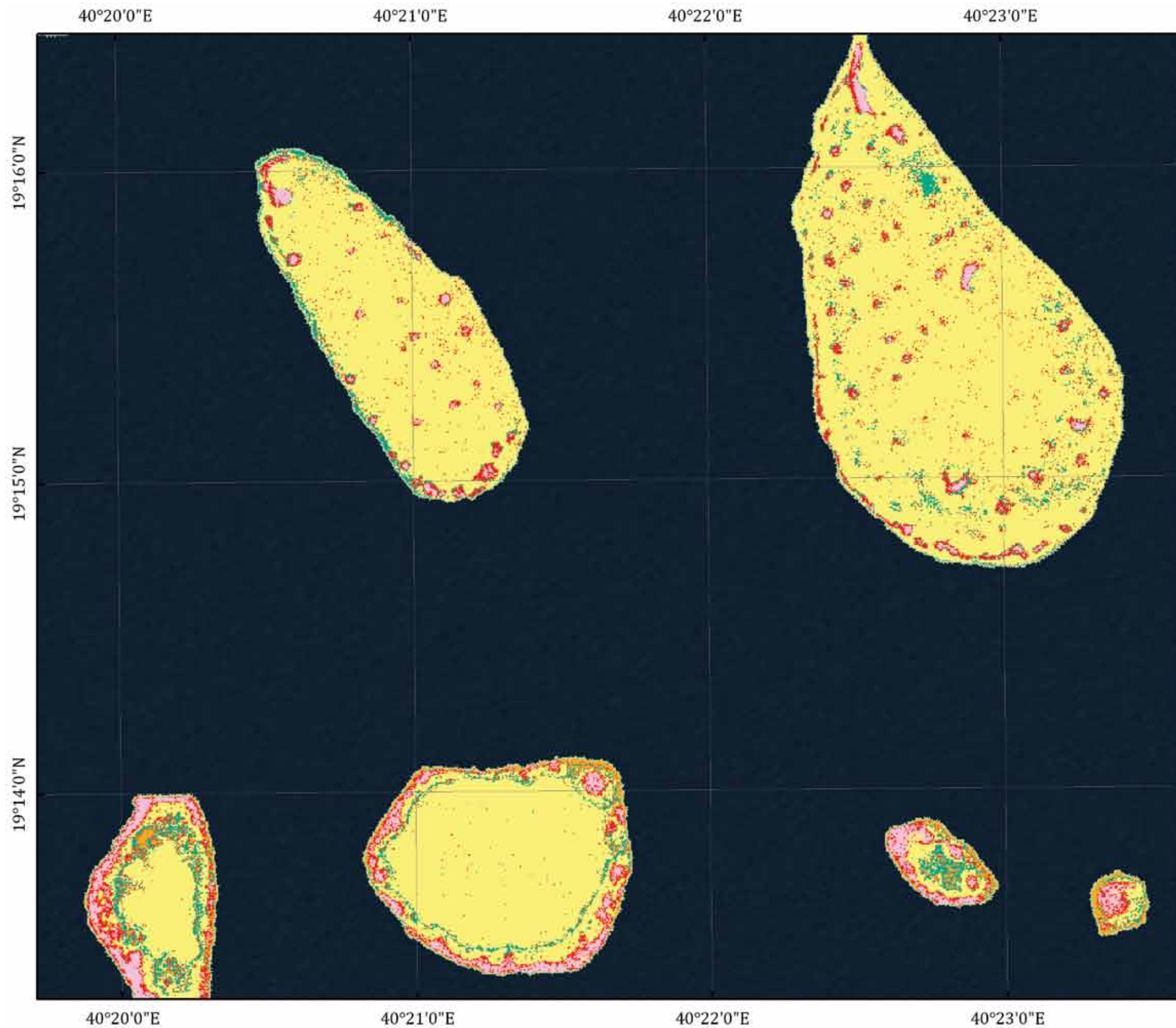




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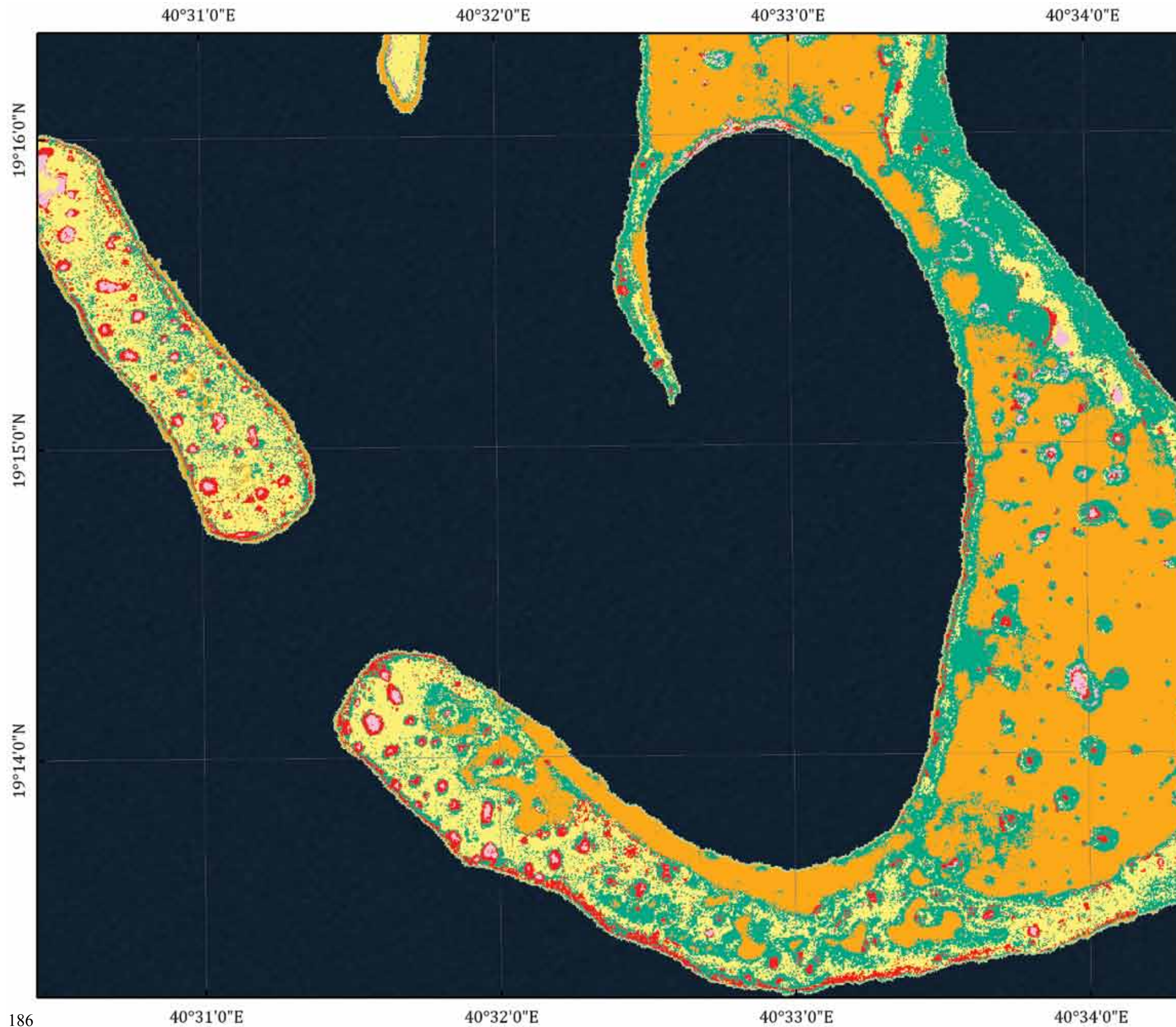


**Farasan Banks Habitats**

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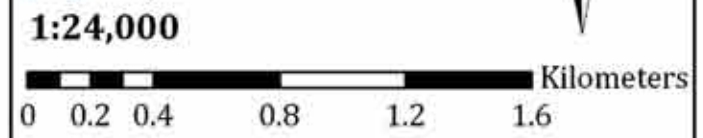
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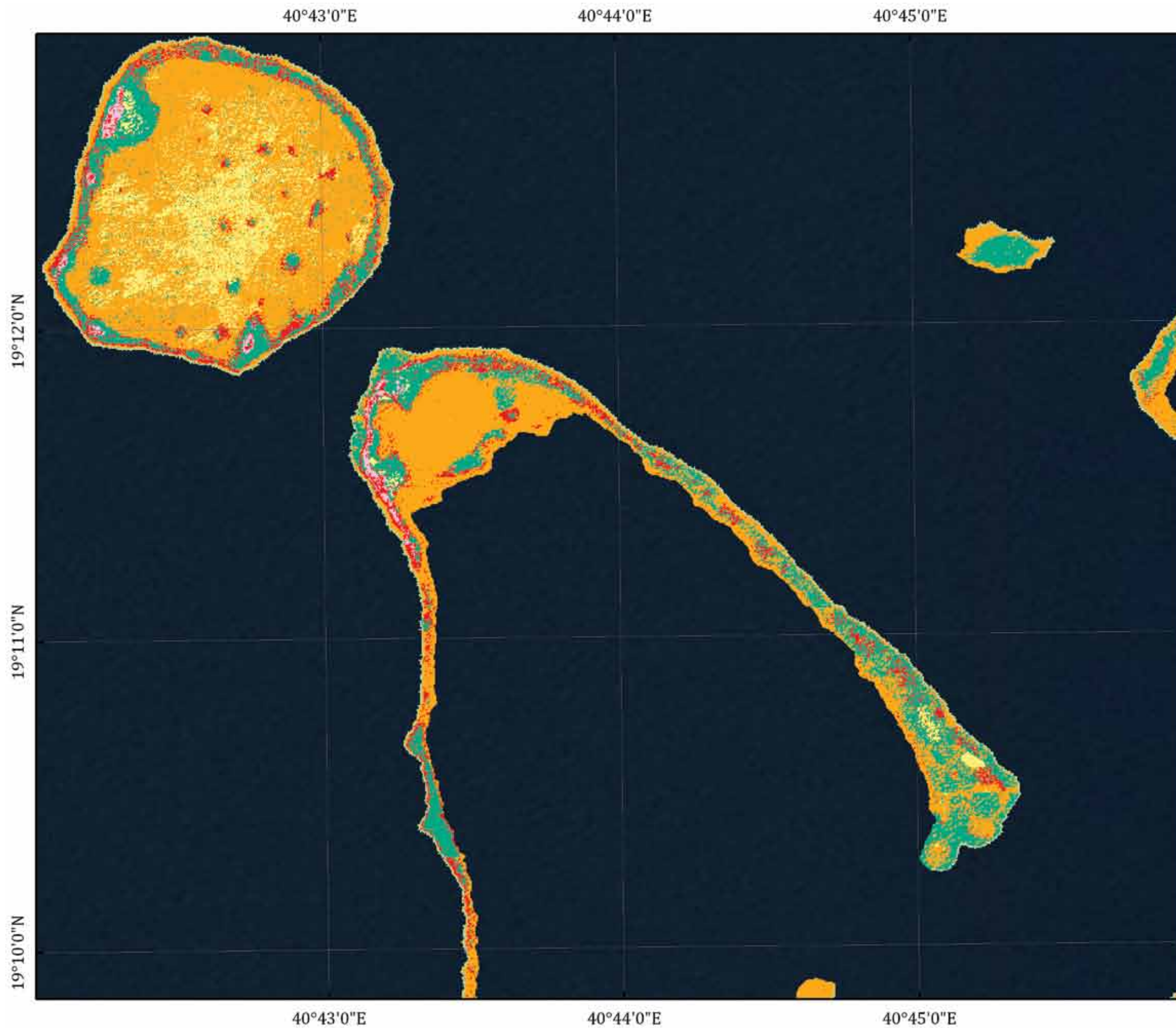
Kilometers



**Farasan Banks Habitats**

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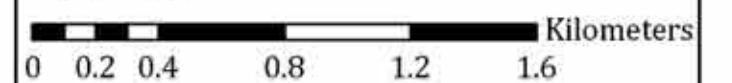


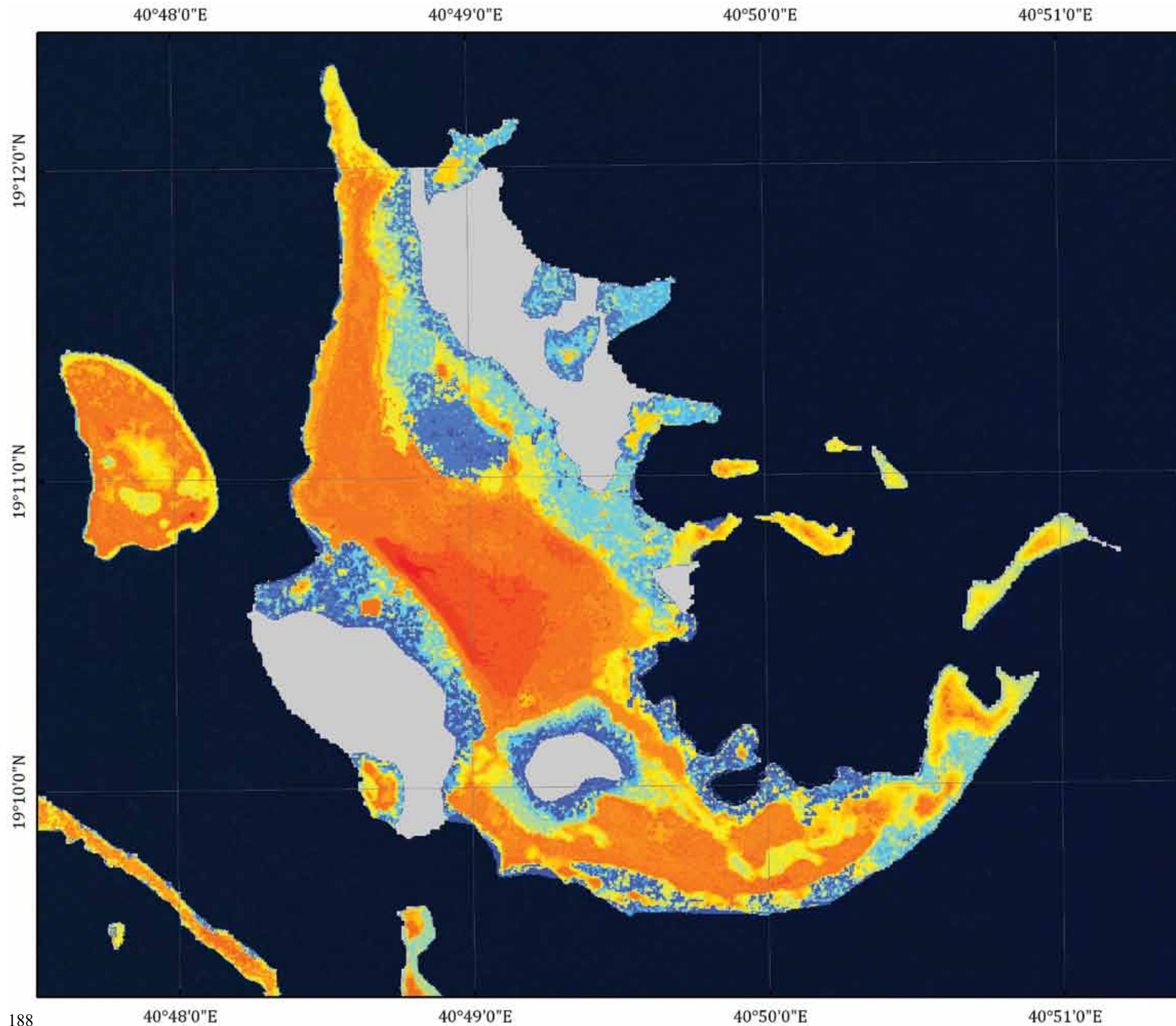


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**1:24,000**





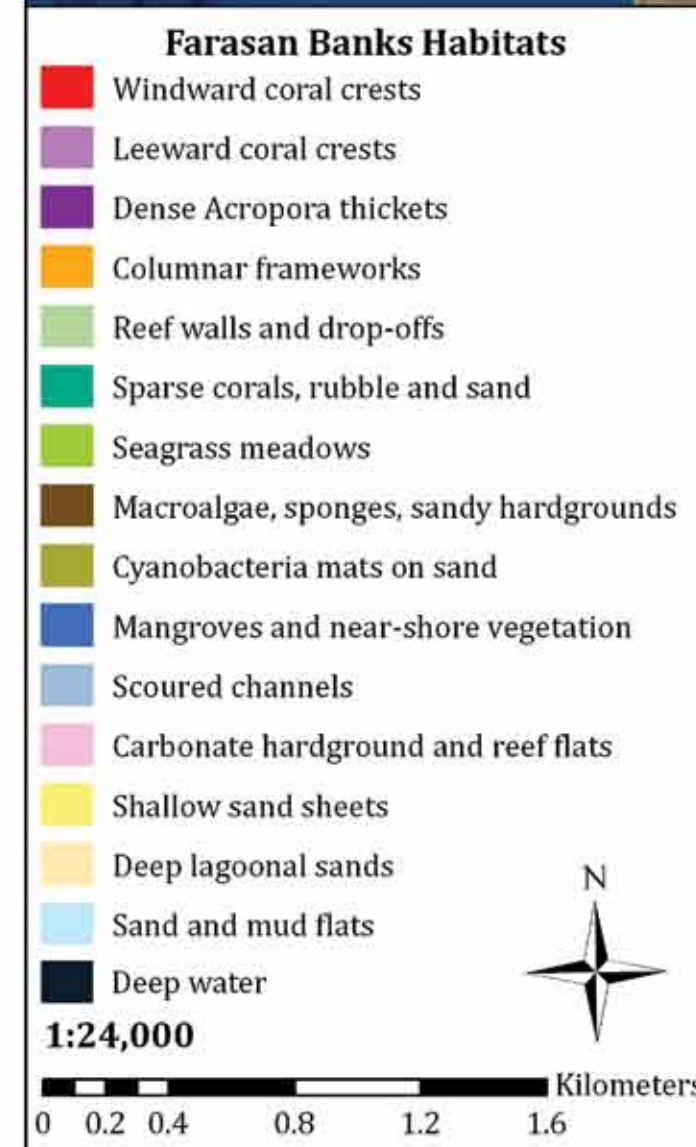
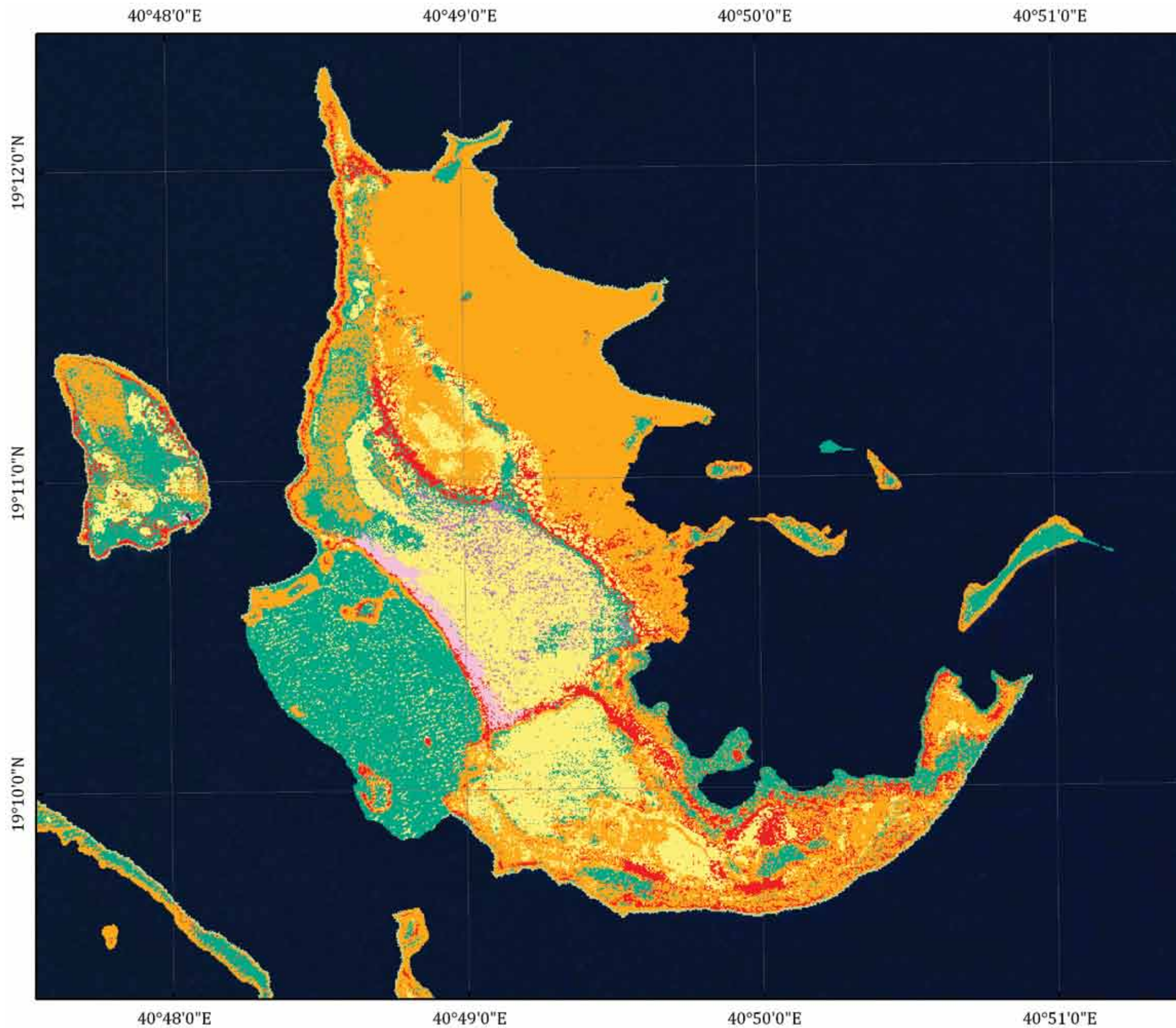
**Farasan Banks Bathymetry**

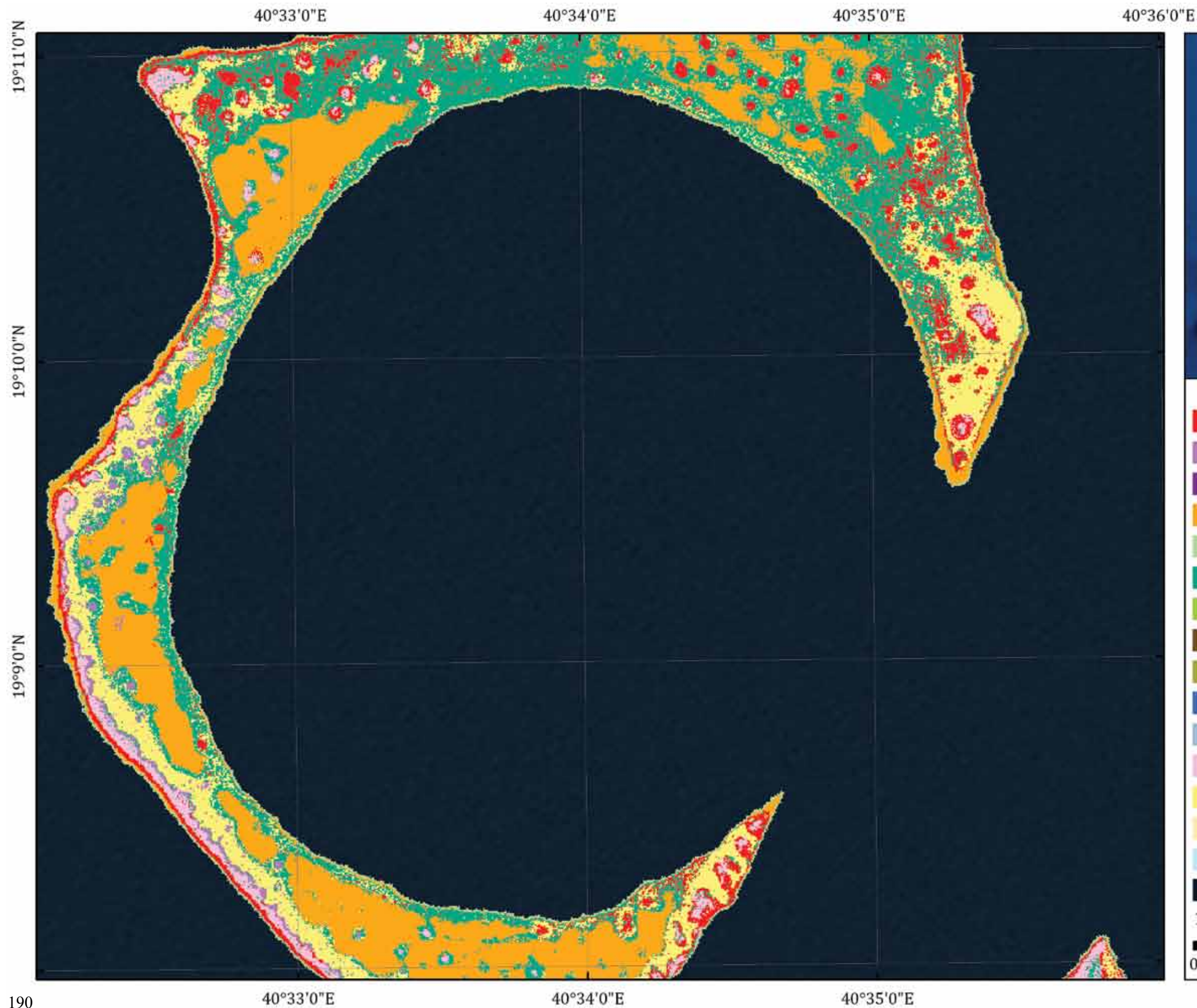
Depth, meters

	0 - 0.9		14 - 14.9
	1 - 1.9		15 - 15.9
	2 - 2.9		16 - 16.9
	3 - 3.9		17 - 17.9
	4 - 4.9		18 - 18.9
	5 - 5.9		19 - 19.9
	6 - 6.9		20 - 20.9
	7 - 7.9		21 - 21.9
	8 - 8.9		22 - 22.9
	9 - 9.9		23 - 23.9
	10 - 10.9		24 - 24.9
	11 - 11.9		25 - 40
	12 - 12.9		Deep water
	13 - 13.9		

**1:24,000**

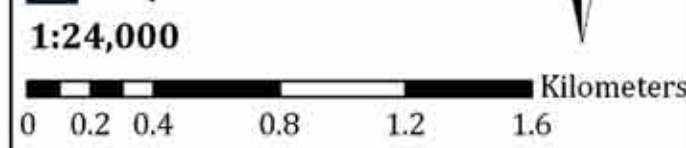


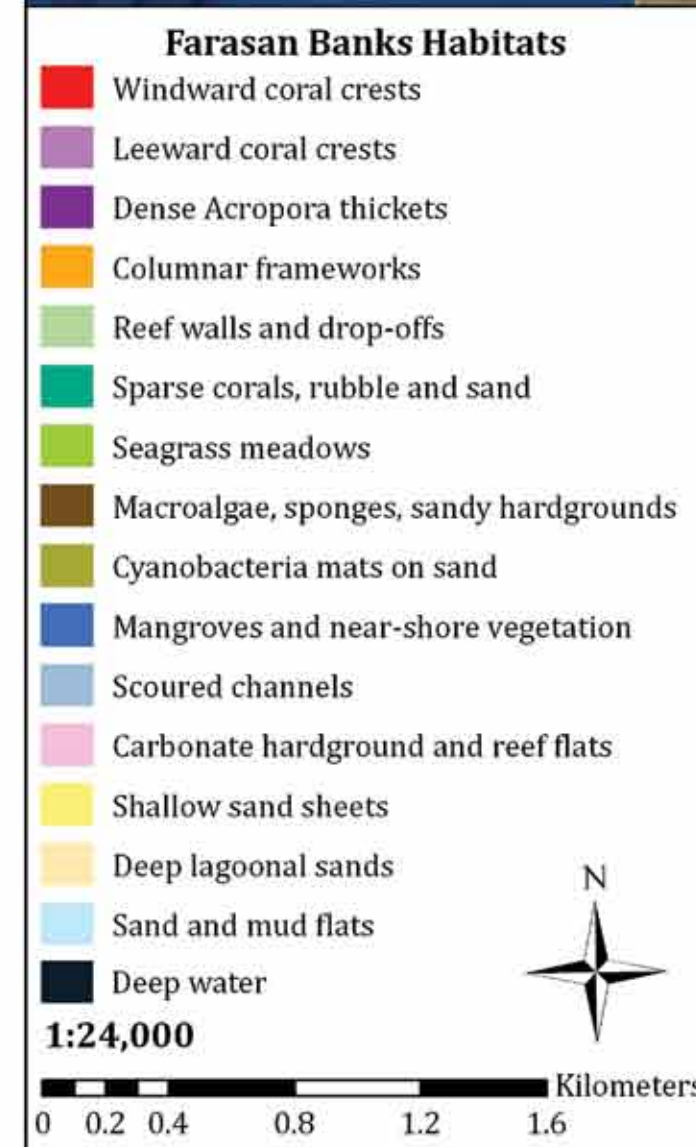
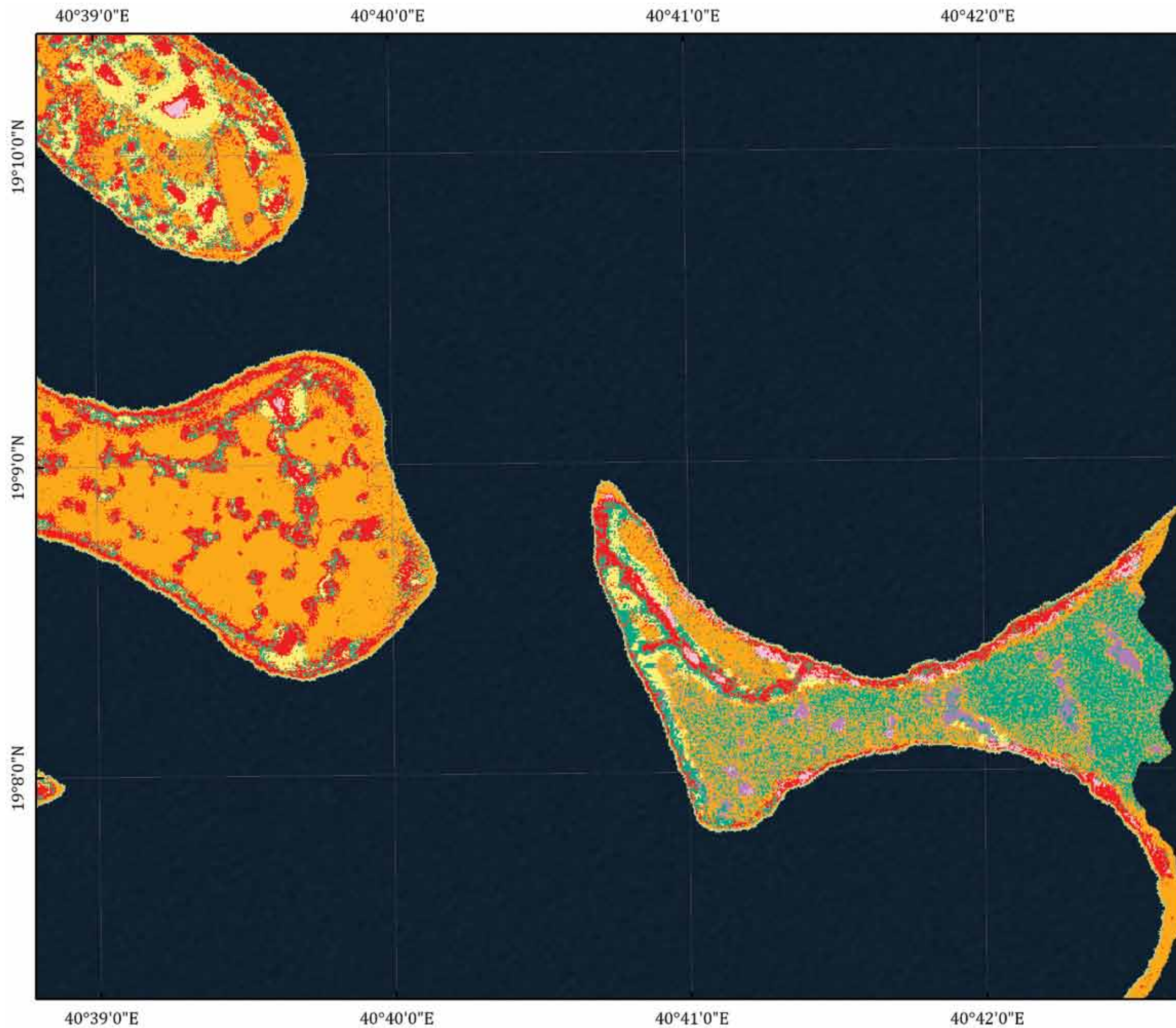




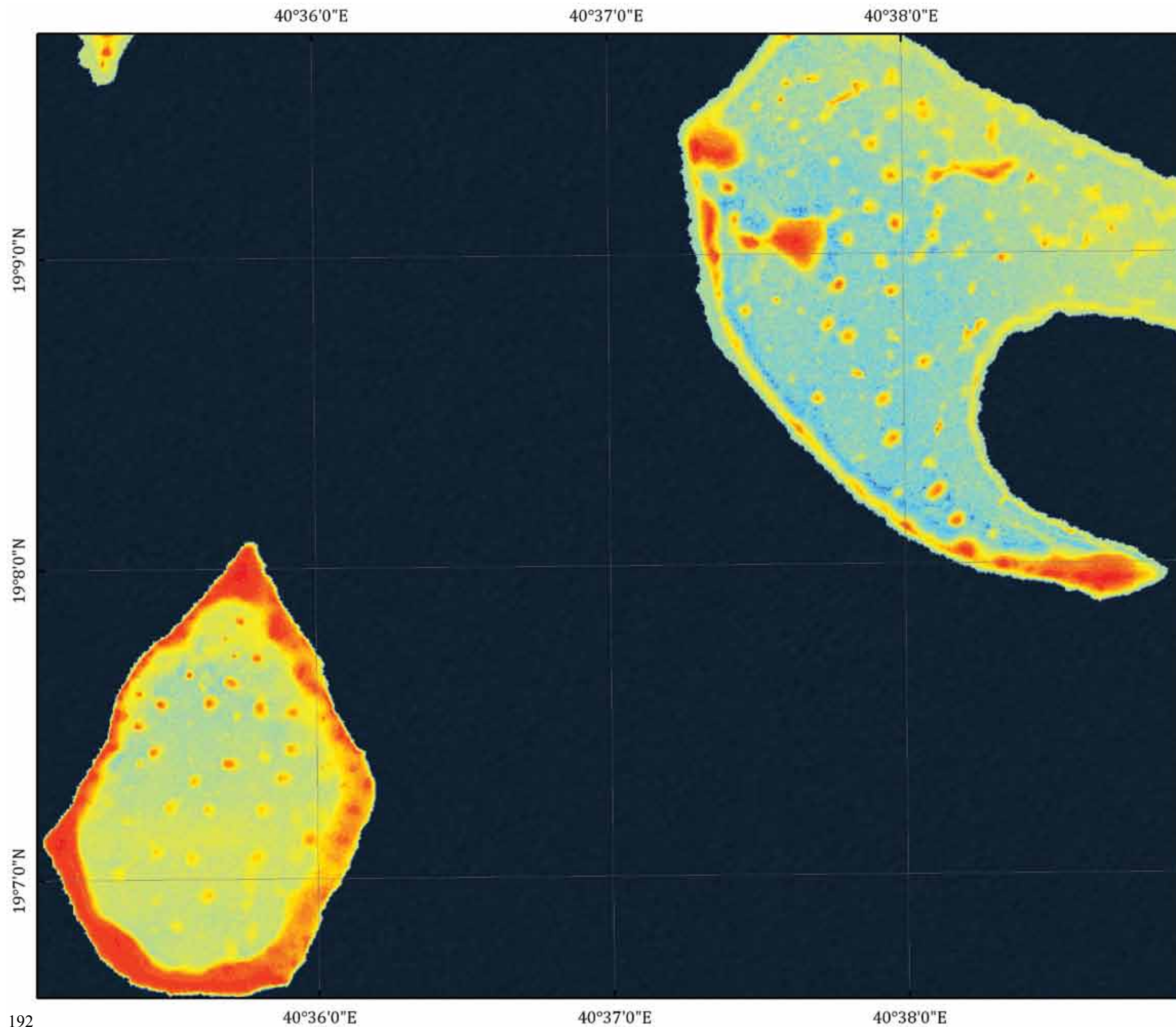
**Farasan Banks Habitats**

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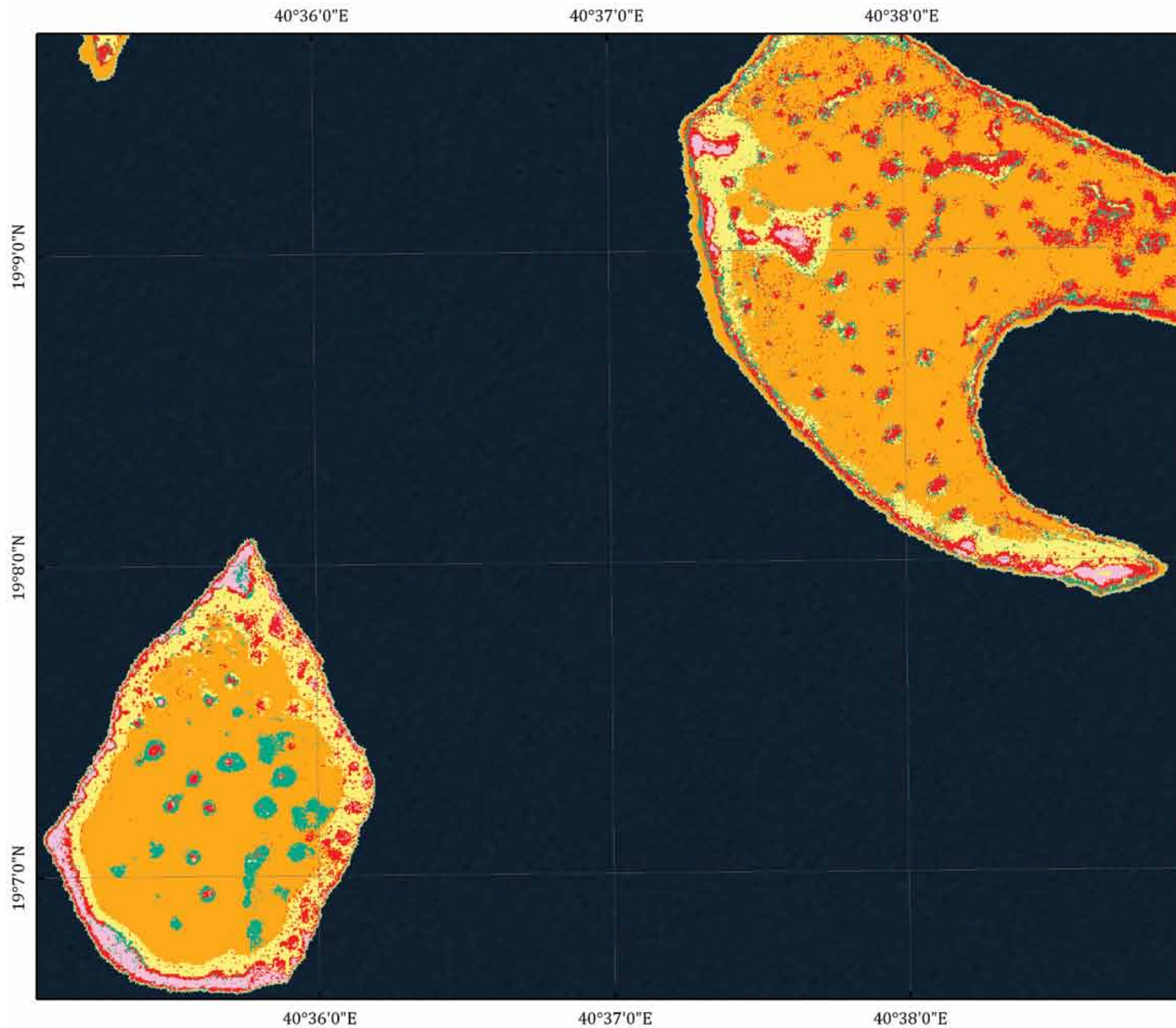
### Farasan Banks Bathymetry

Depth, meters

0 - 0.9	14 - 14.9
1 - 1.9	15 - 15.9
2 - 2.9	16 - 16.9
3 - 3.9	17 - 17.9
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5 - 5.9	19 - 19.9
6 - 6.9	20 - 20.9
7 - 7.9	21 - 21.9
8 - 8.9	22 - 22.9
9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	

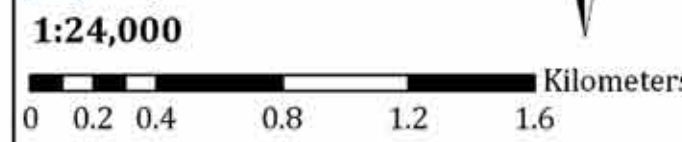
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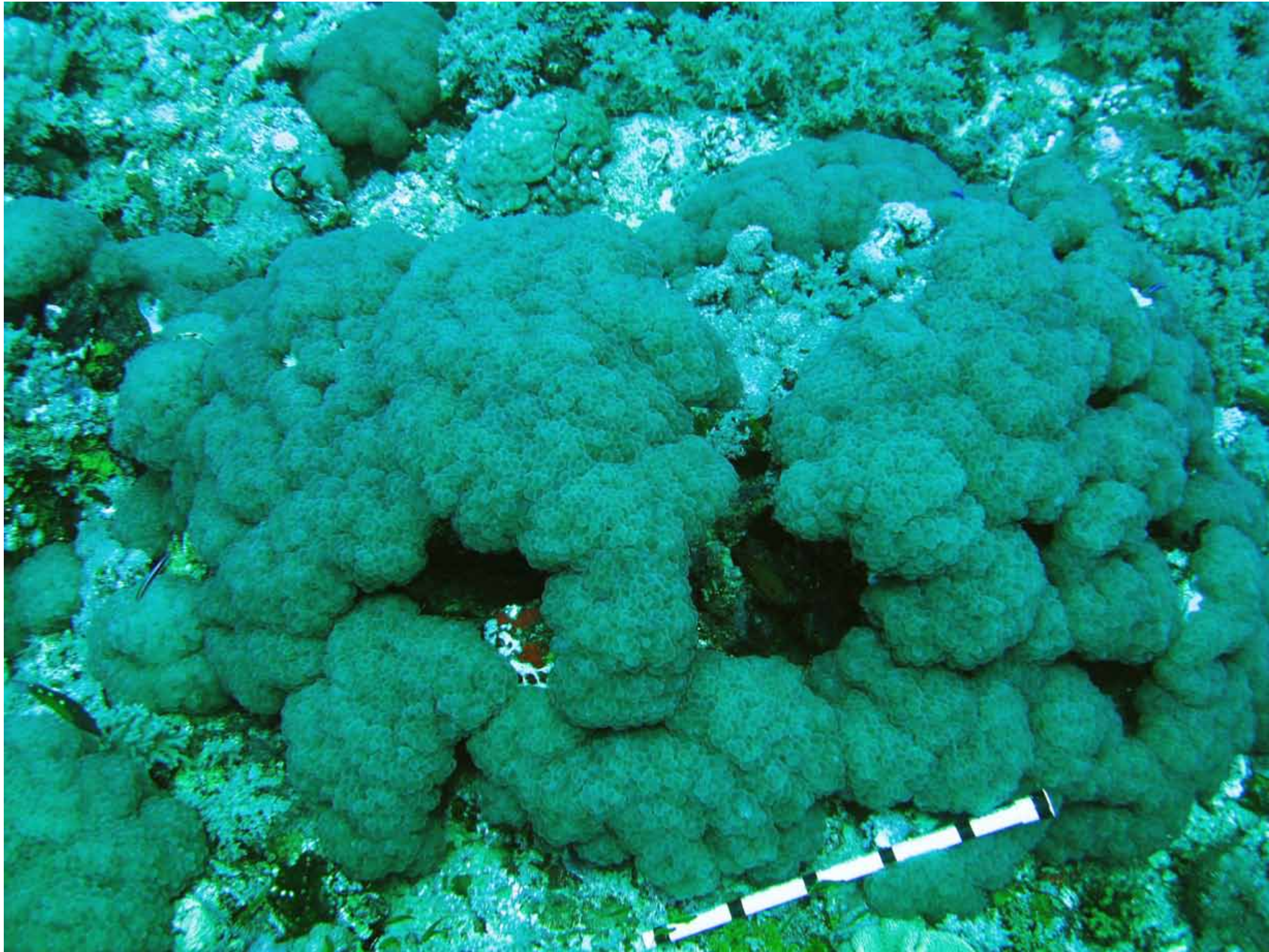




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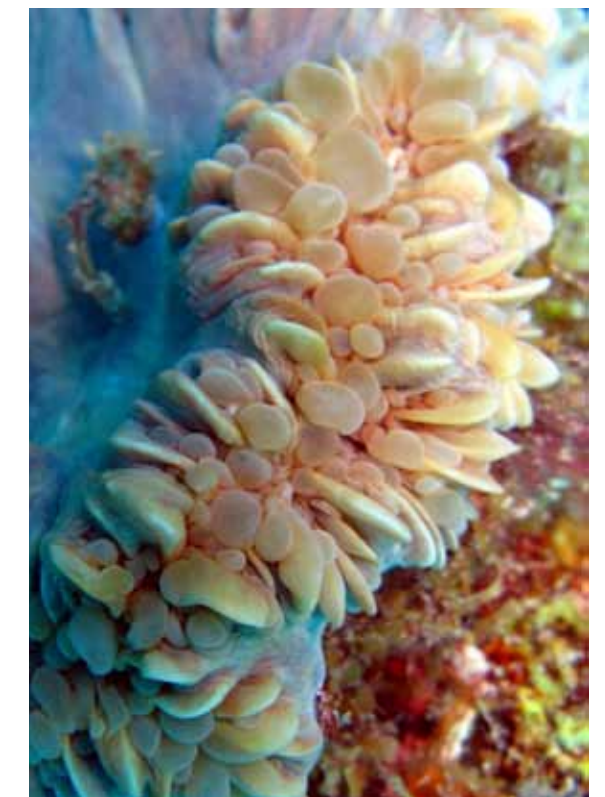




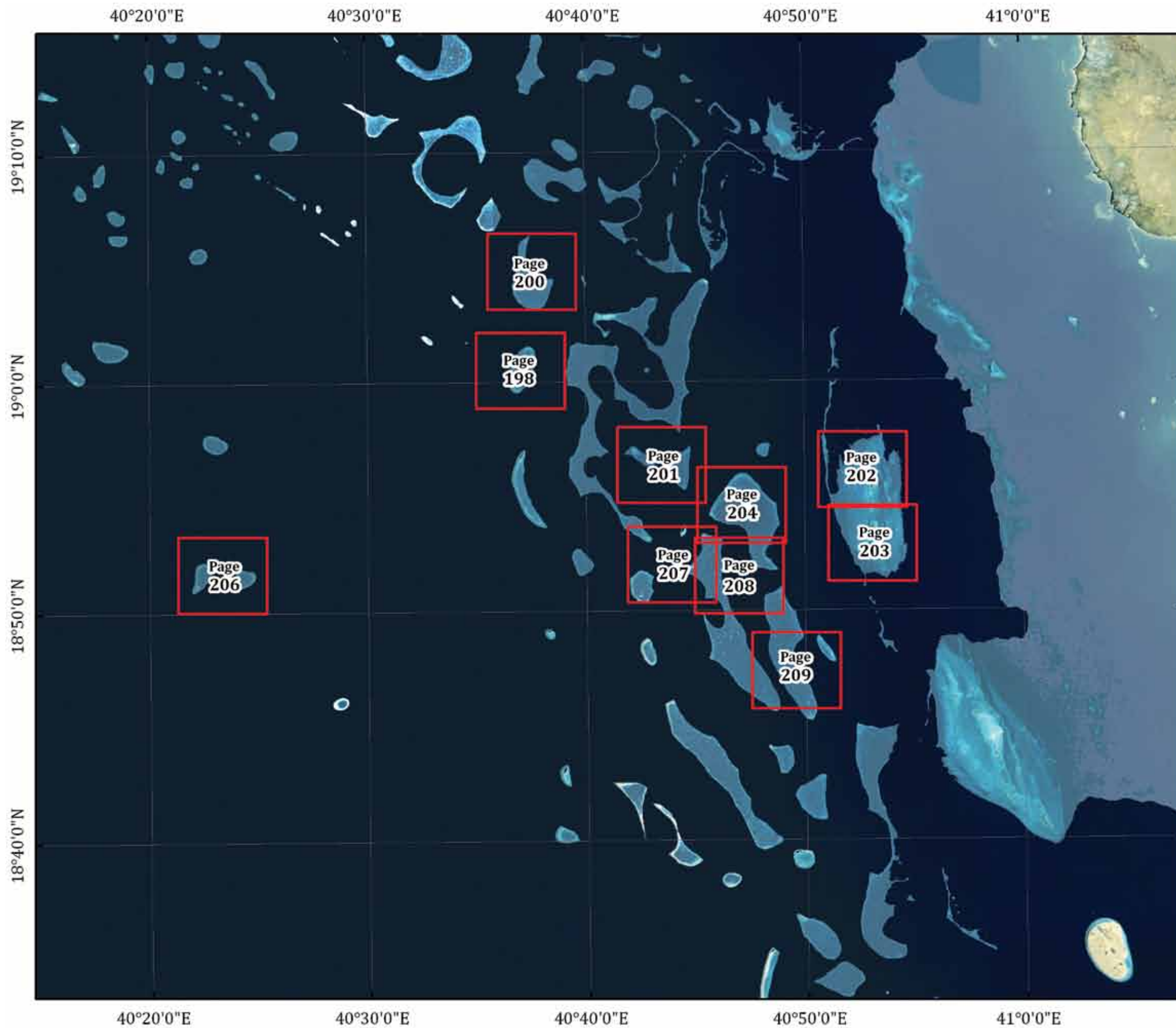
On one of the submerged offshore reefs in the northern Farasan Banks, an unusual occurrence of *Plerogyra sinuosa* (bubble coral) was found. Colonies formed a monospecific assemblage that extended several hundred meters along a reef slope, from over 40 m depth to about 20 m depth. Live coral cover ranged from about 50-80%, with individual colonies exceeding 5 m in diameter. The colony above is about 2 m wide; scale bar is 50 cm.

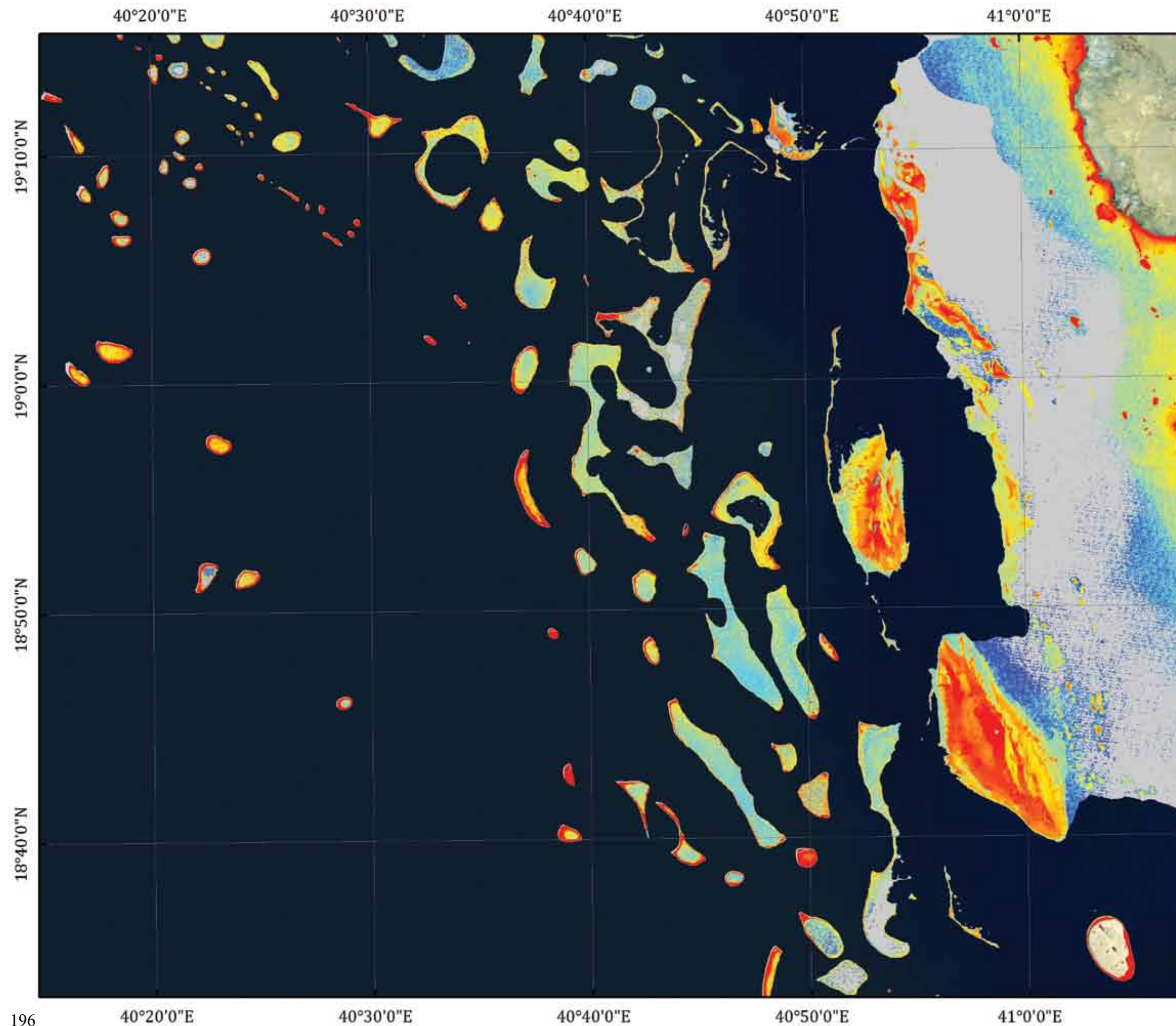


Closeup of *Plerogyra sinuosa* showing the phaceloid growth form and the characteristic bubble-like vesicles.



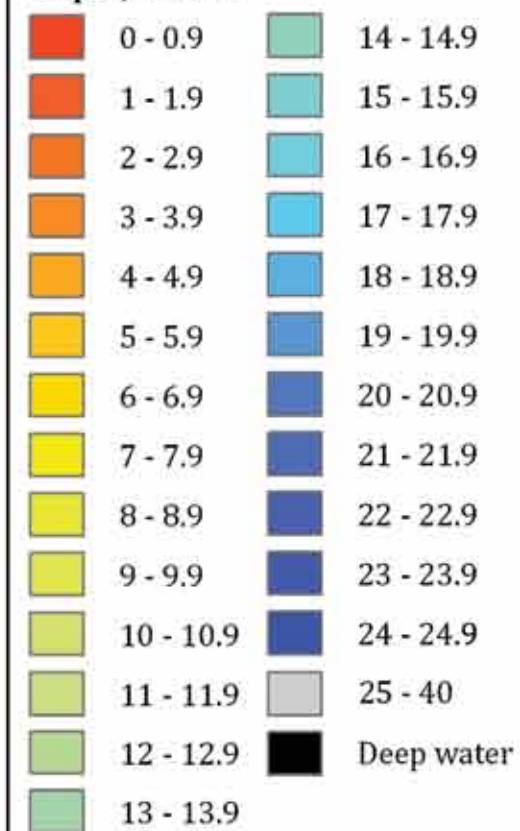
Closeup of a partially retracted colony of *Plerogyra sinuosa*. The prominent exsert skeletal elements (septa) and a few vesicles are visible.





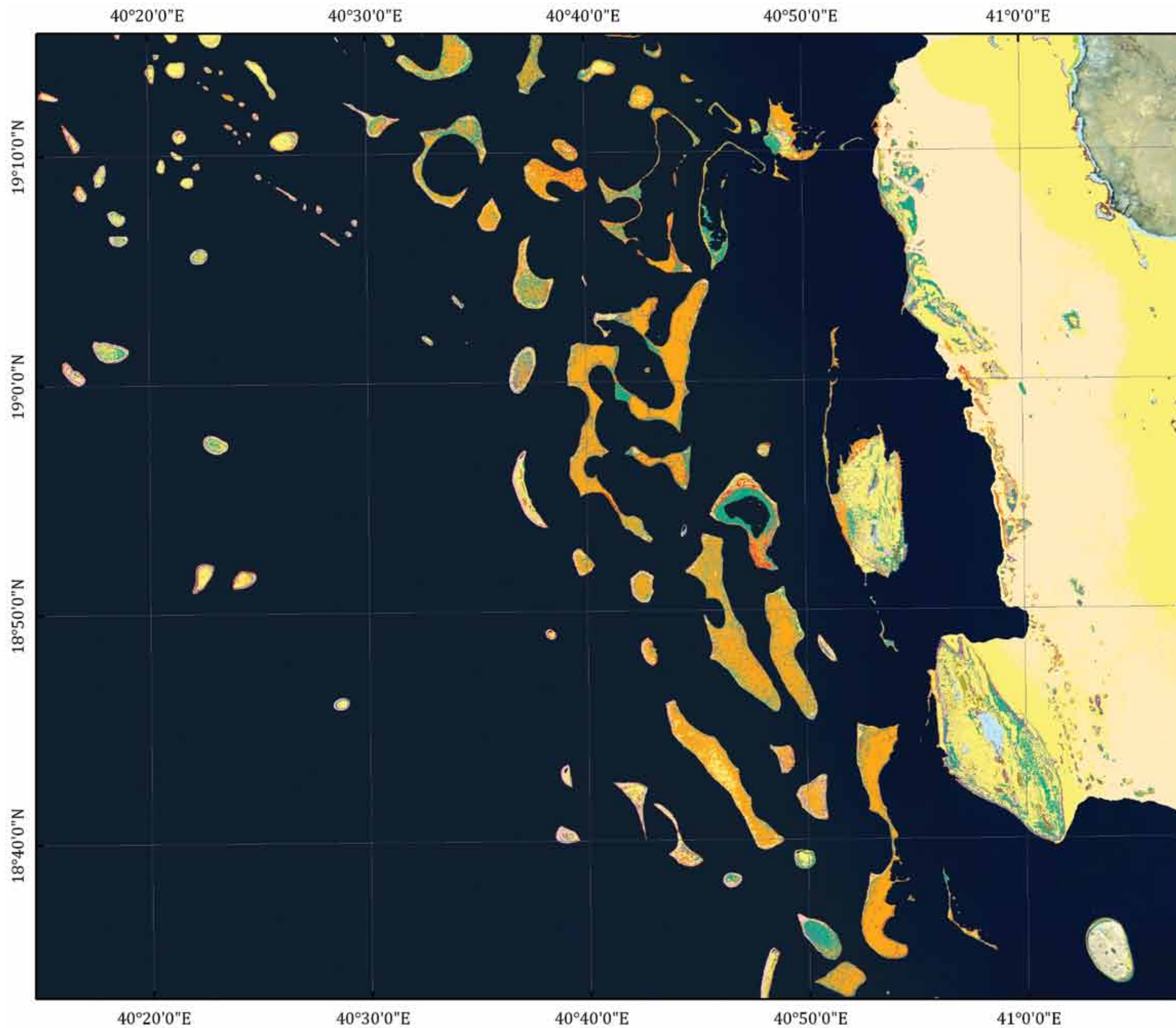
**Farasan Banks Bathymetry**

Depth, meters



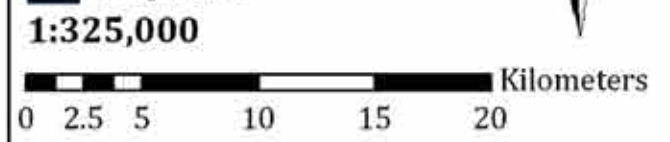
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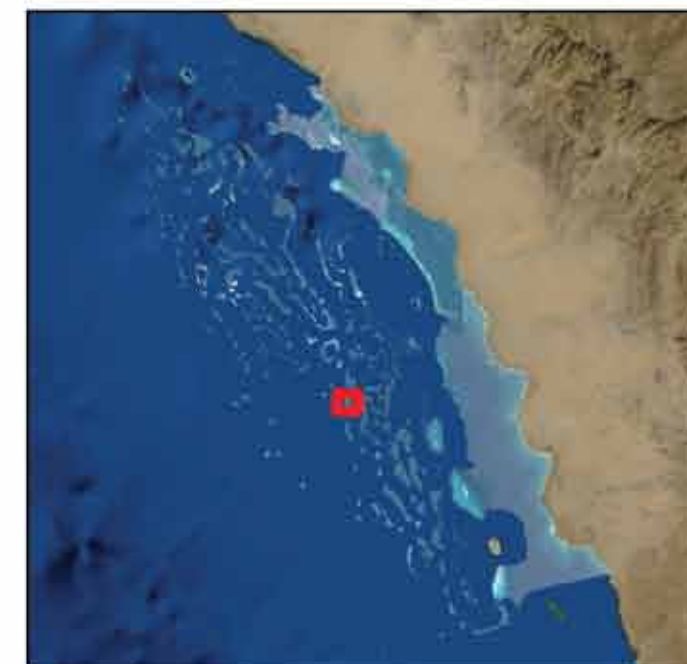
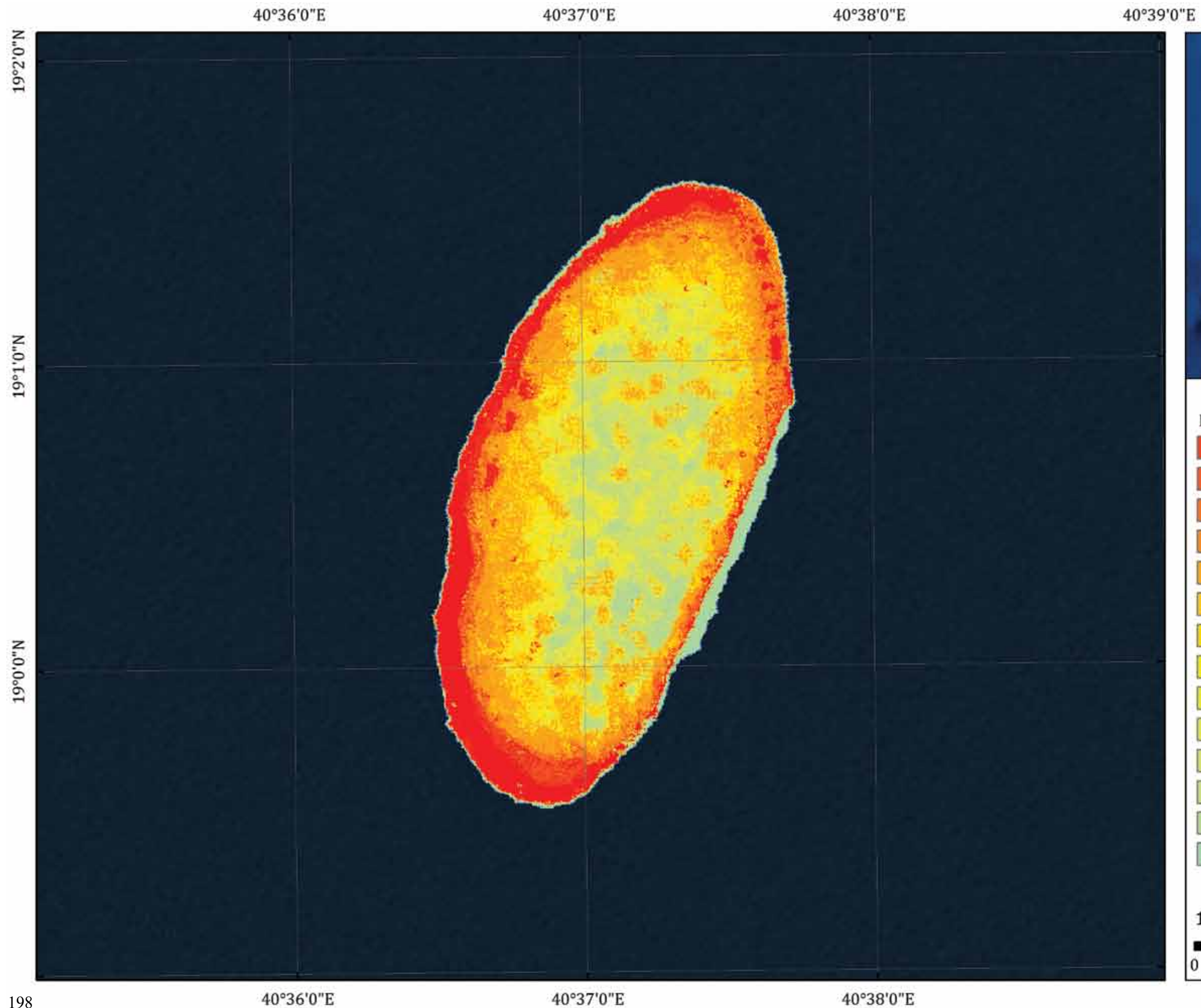




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**Farasan Banks Bathymetry**

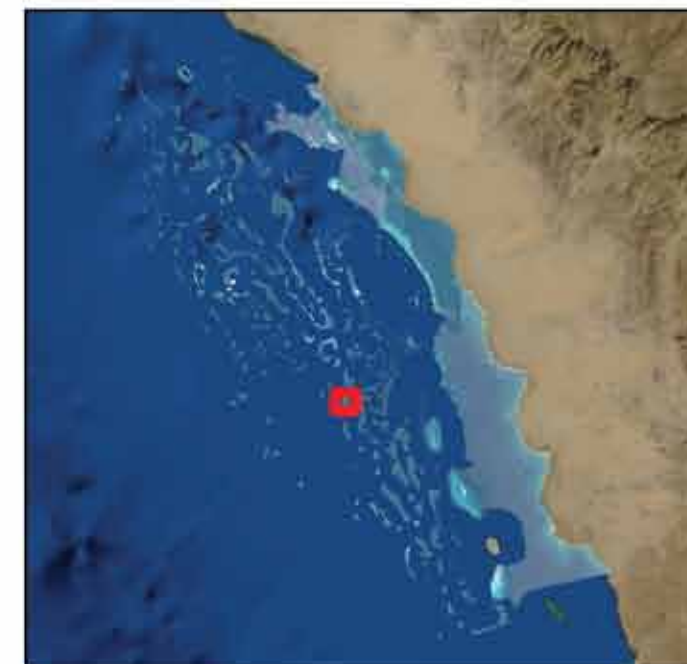
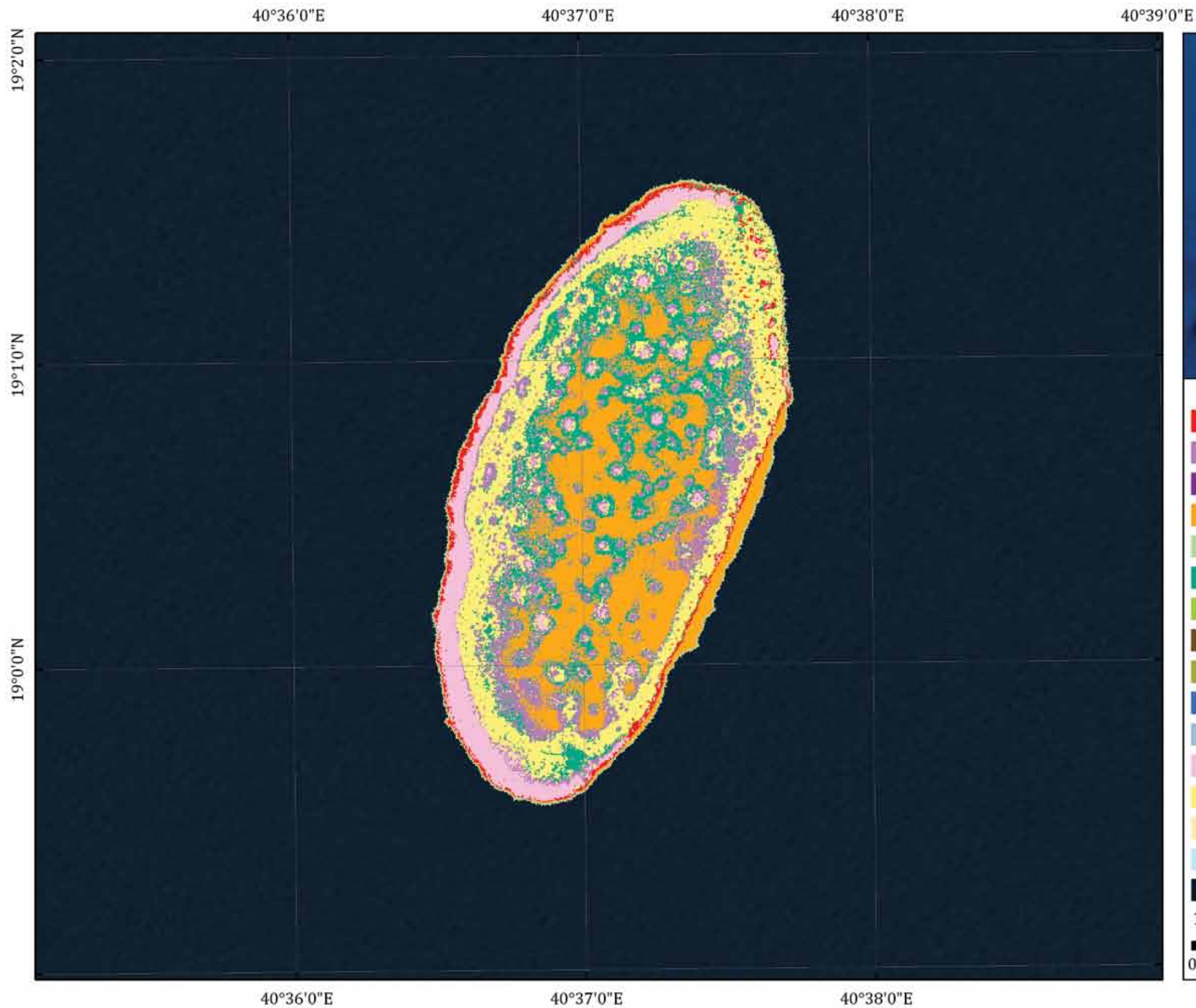
Depth, meters

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9 - 9.9	23 - 23.9
10 - 10.9	24 - 24.9
11 - 11.9	25 - 40
12 - 12.9	Deep water
13 - 13.9	



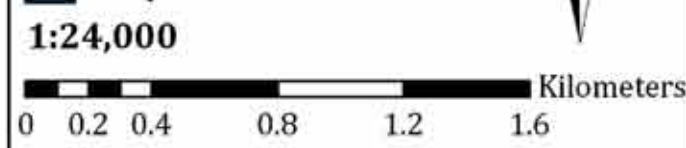
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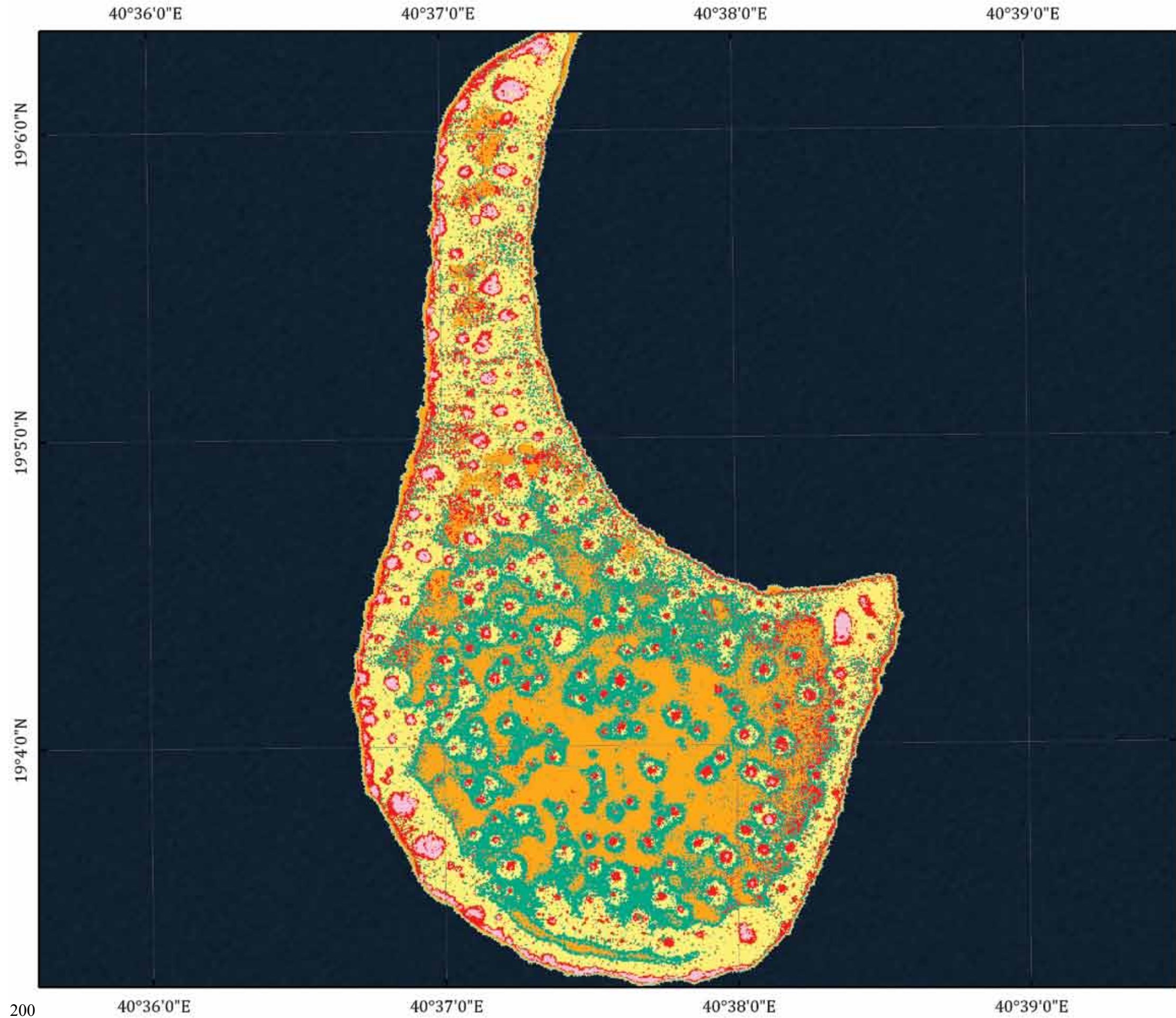


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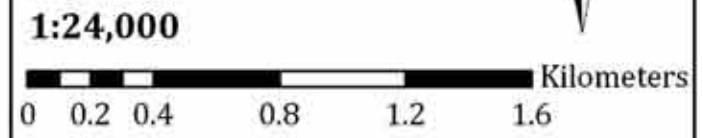


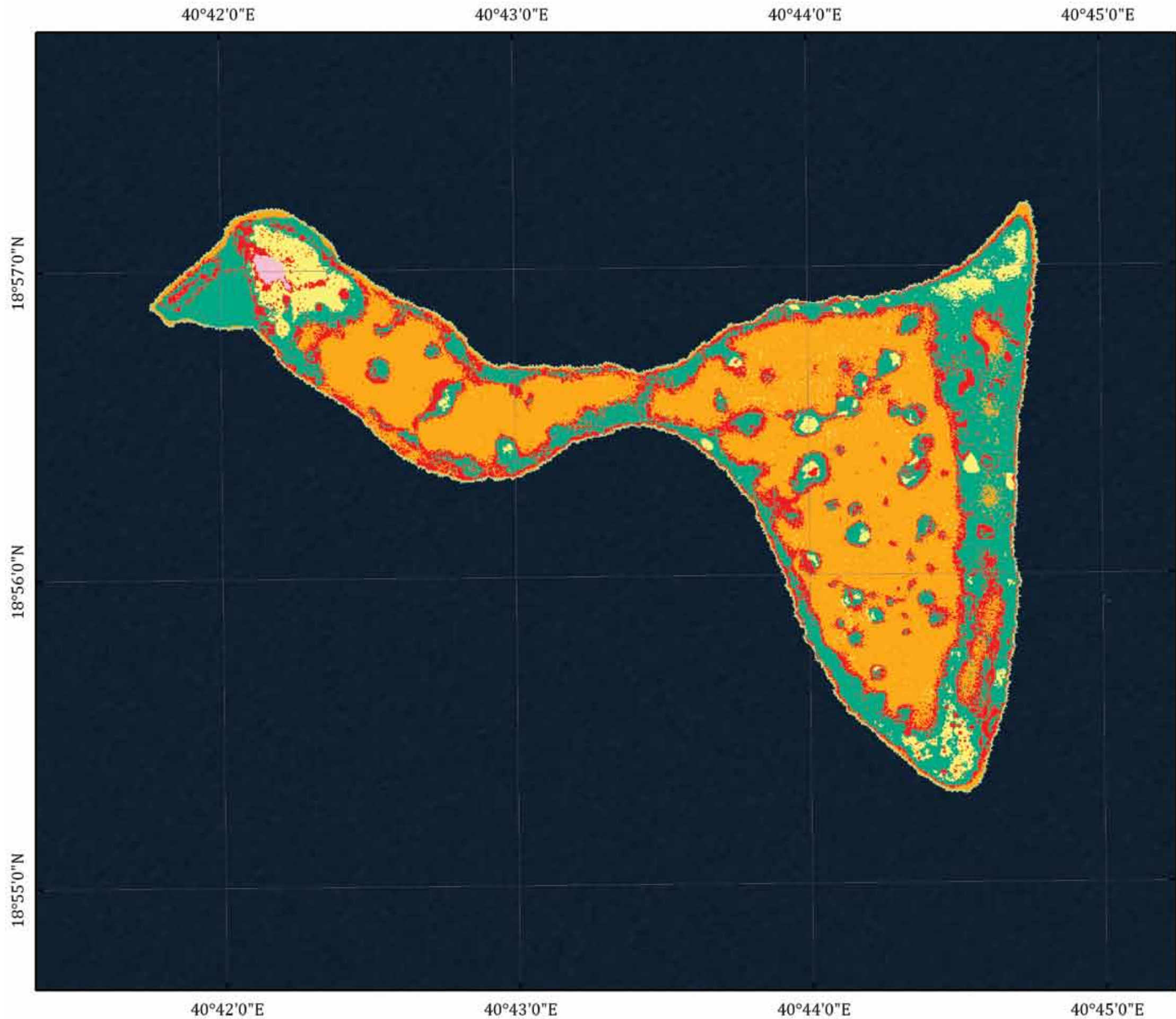




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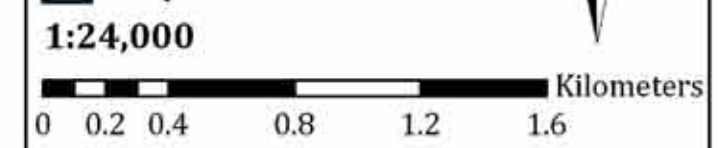
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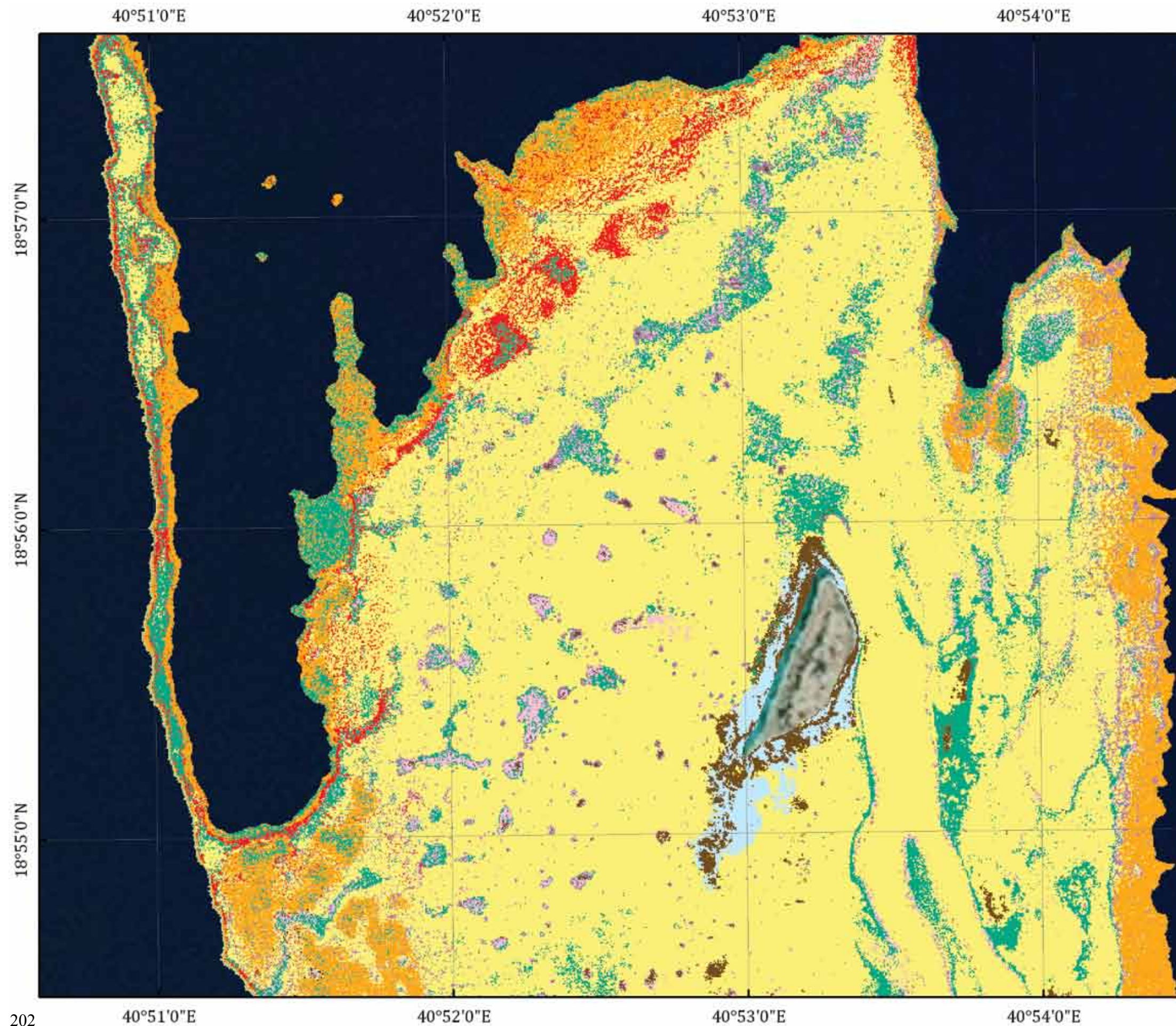




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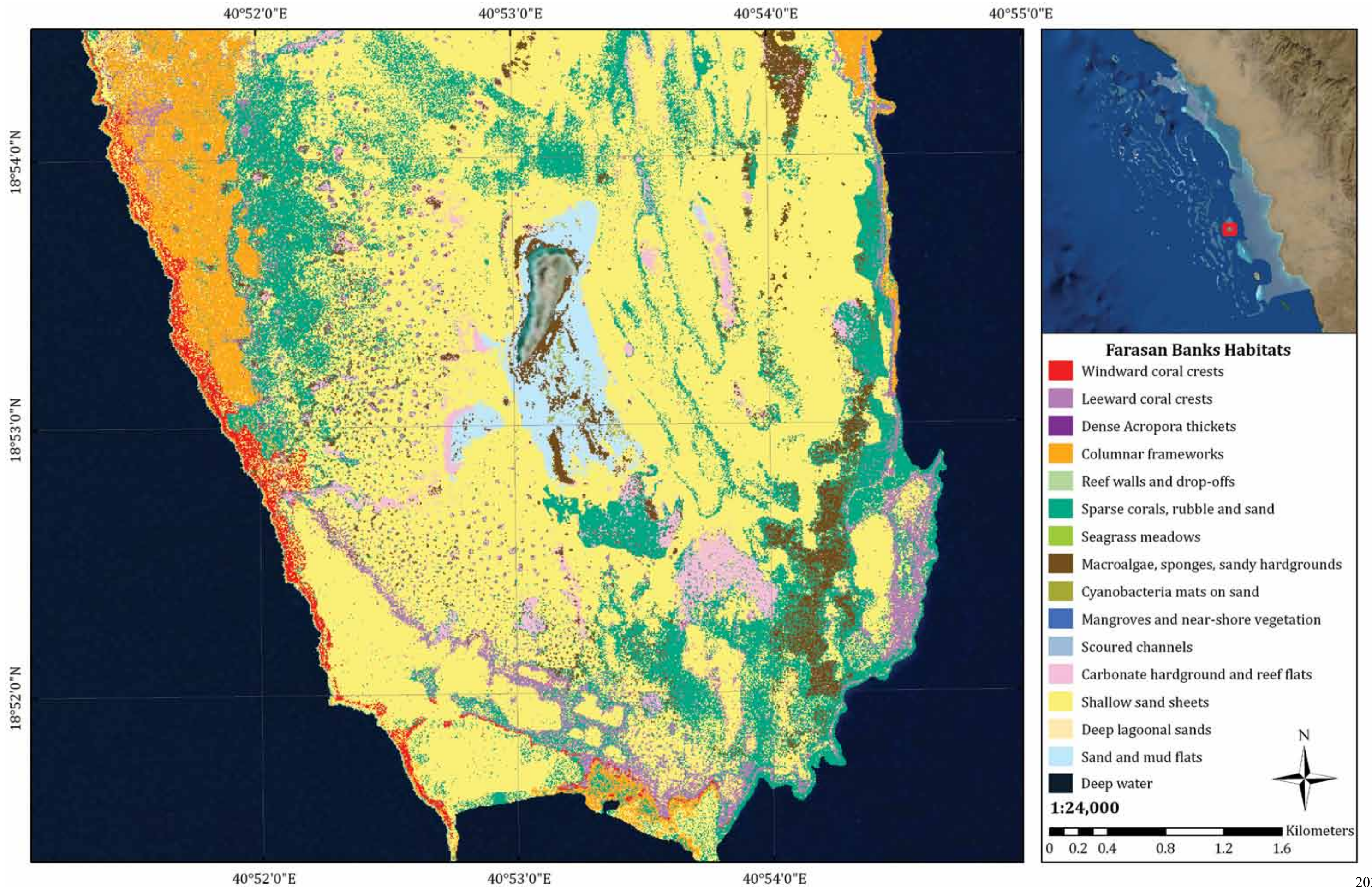


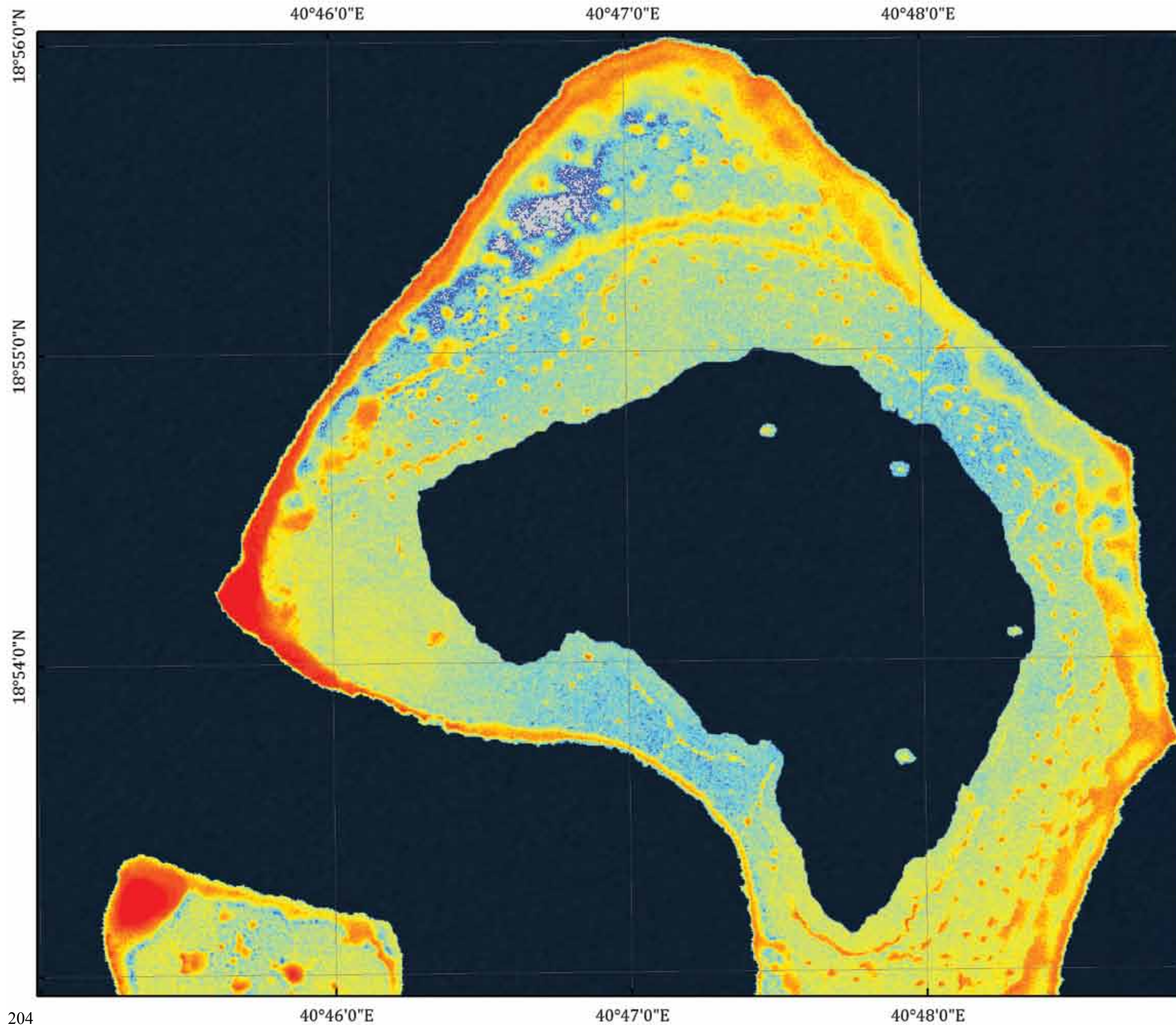
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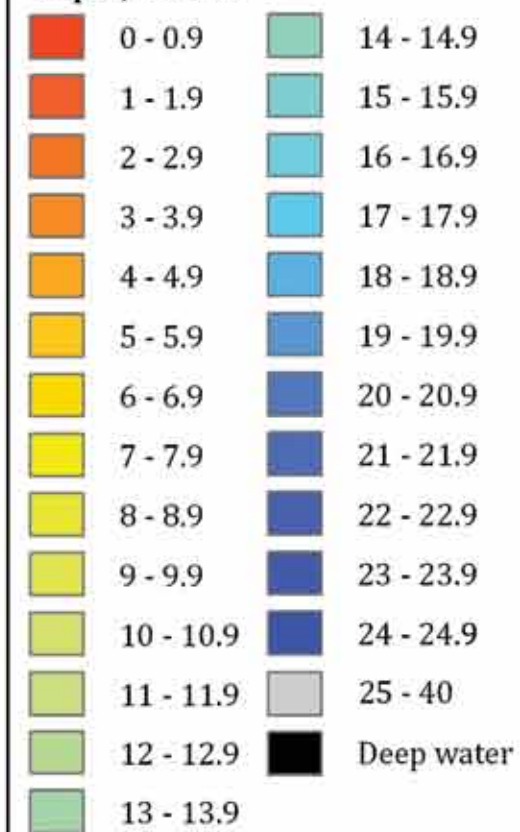






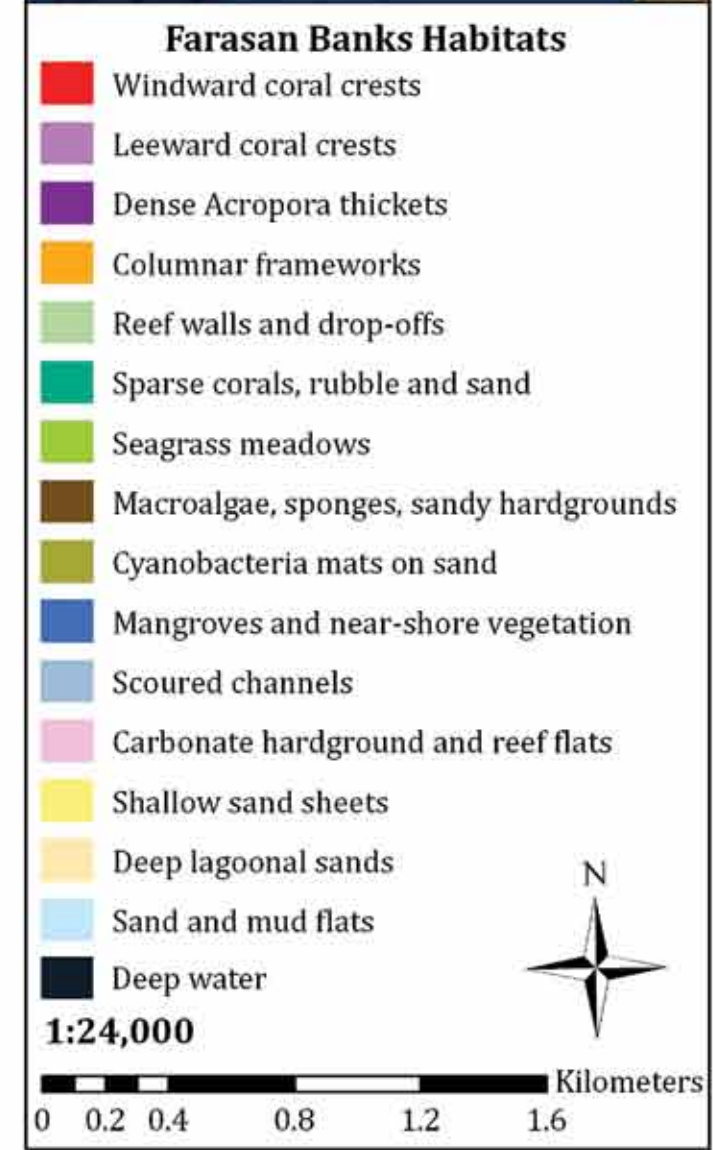
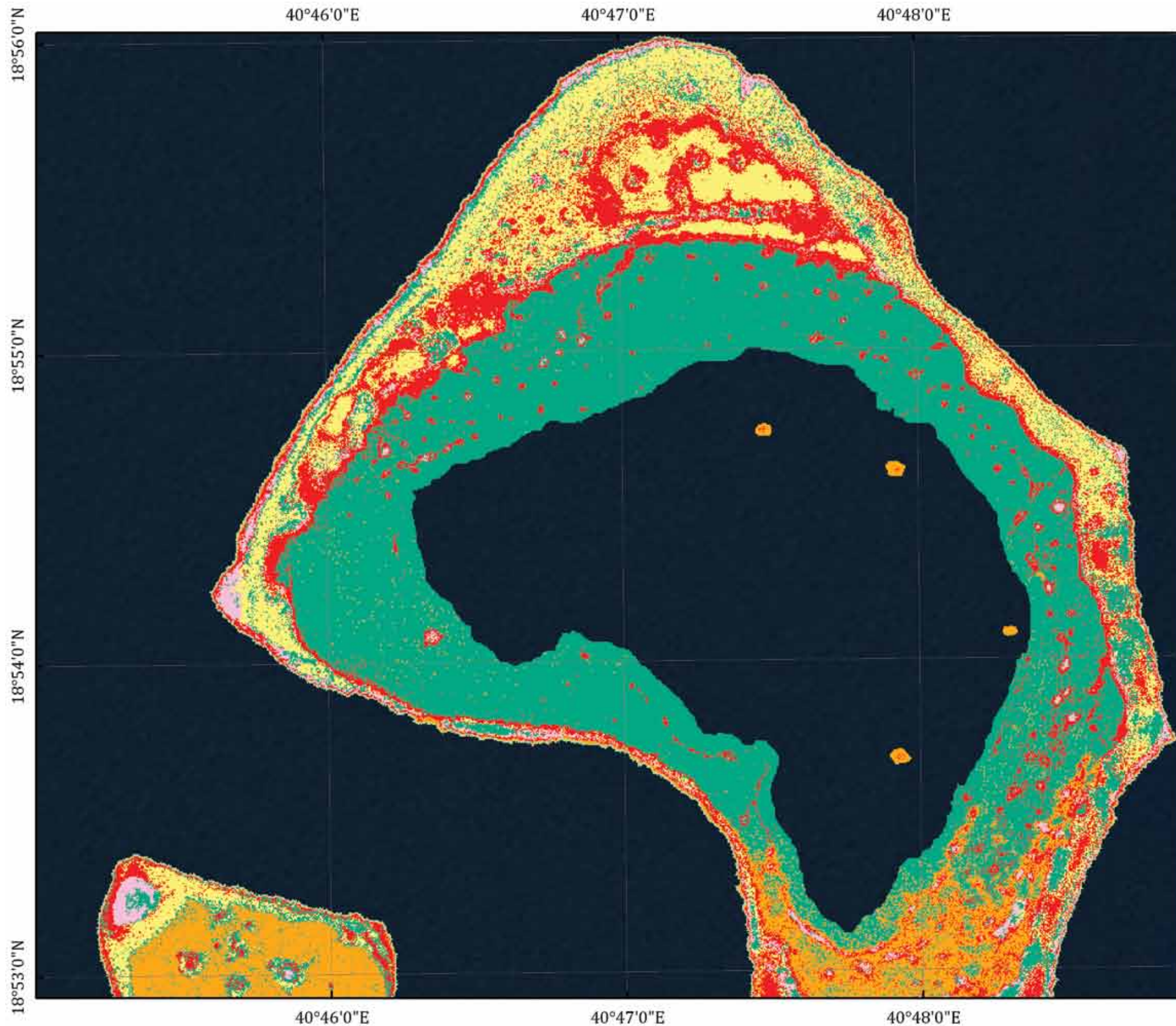
**Farasan Banks Bathymetry**

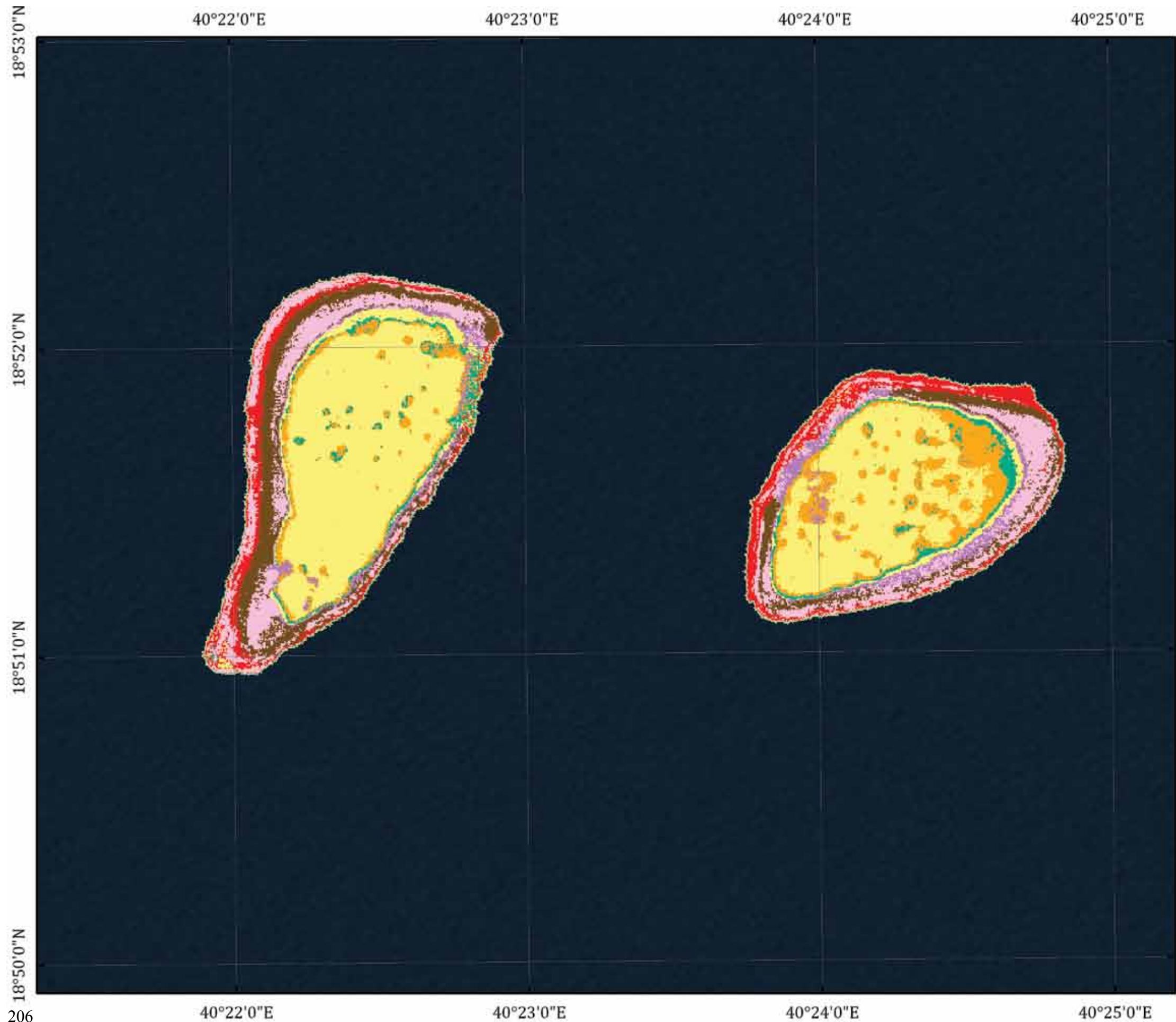
Depth, meters



**1:24,000**

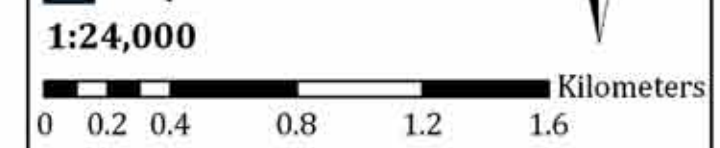






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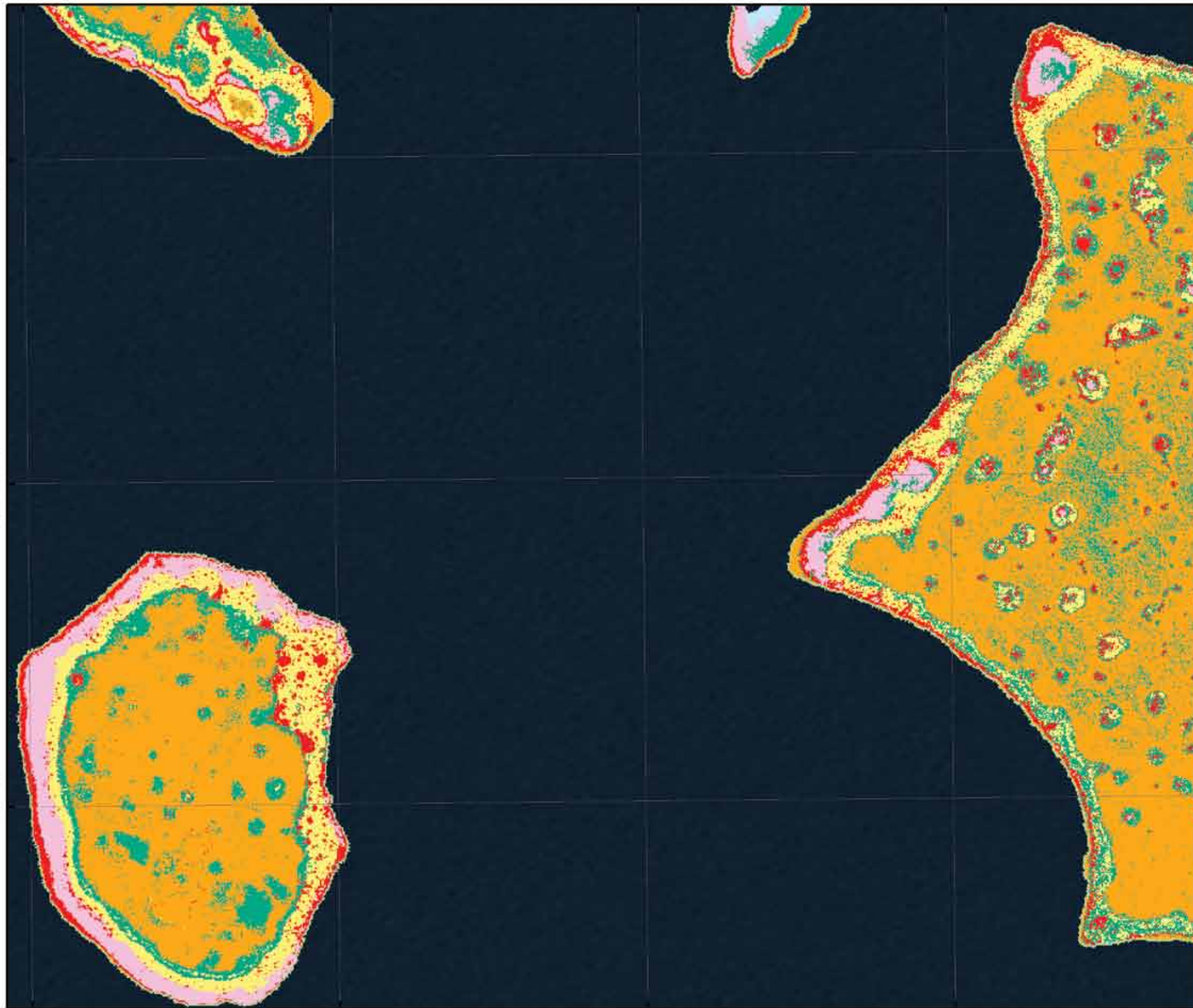


40°42'0"E      40°43'0"E      40°44'0"E      40°45'0"E

18°53'0"N

18°52'0"N

18°51'0"N



40°43'0"E

40°44'0"E

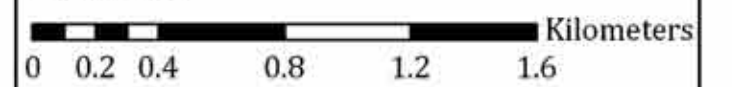
40°45'0"E



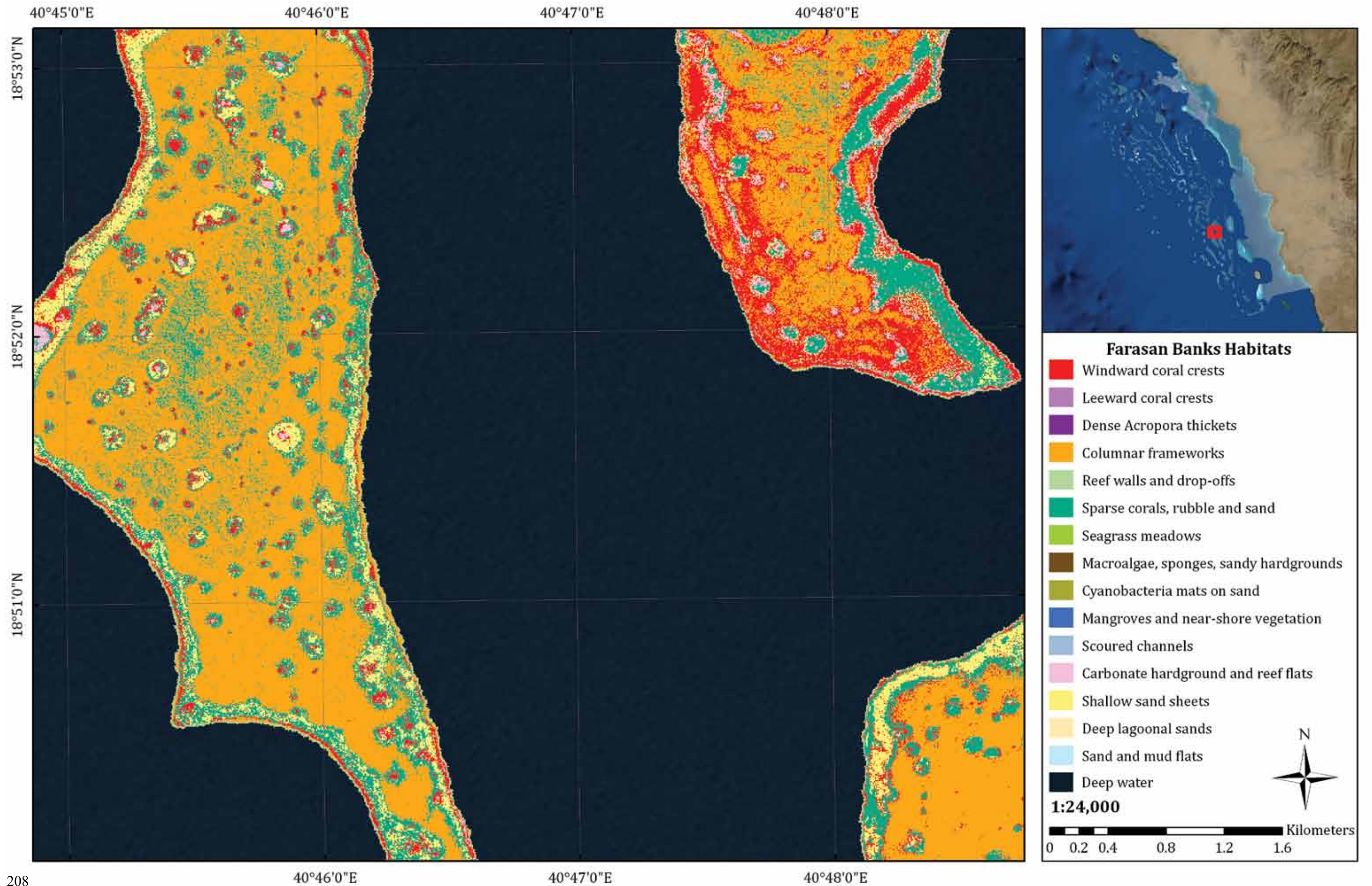
### Farasan Banks Habitats

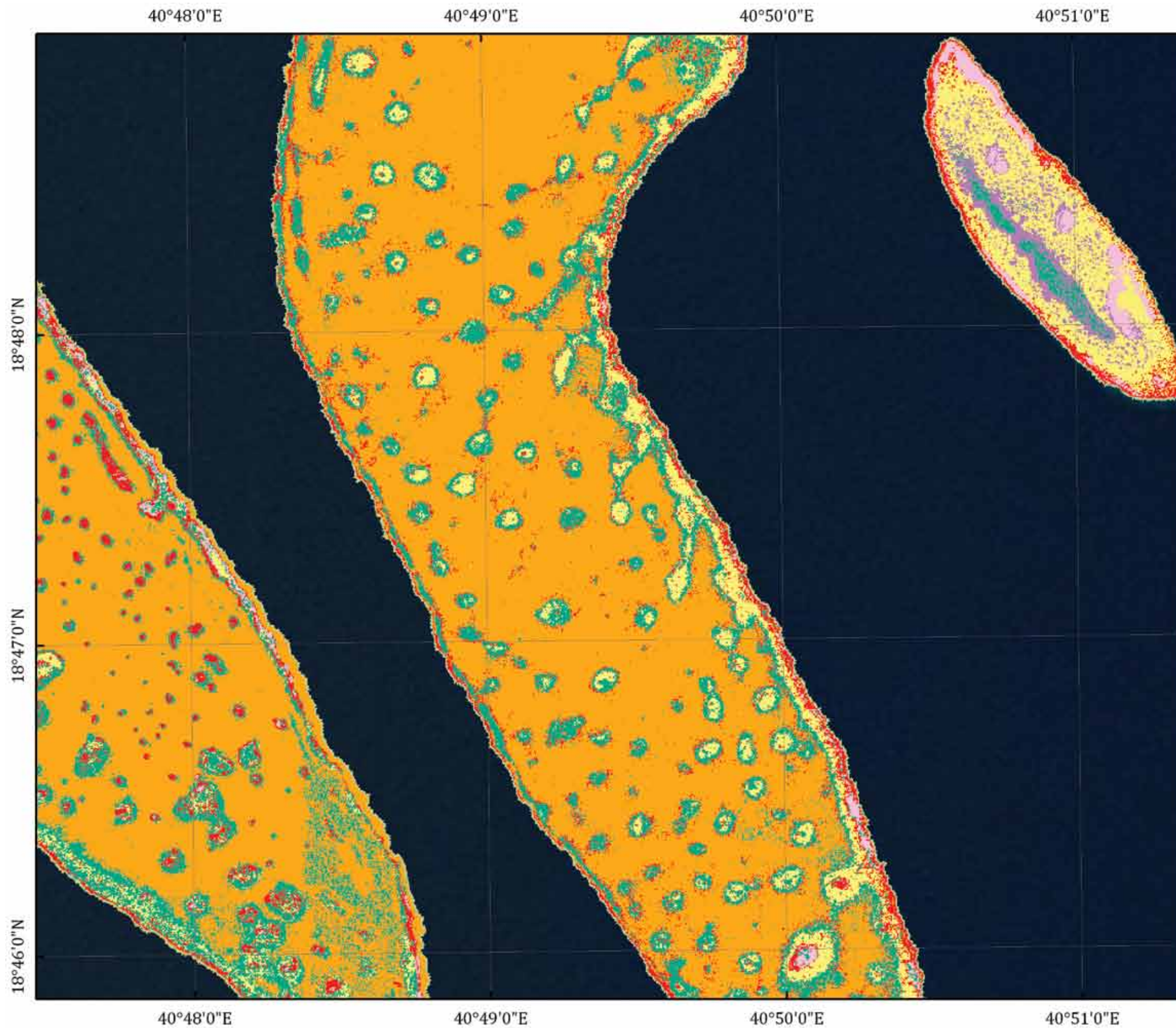
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1:24,000







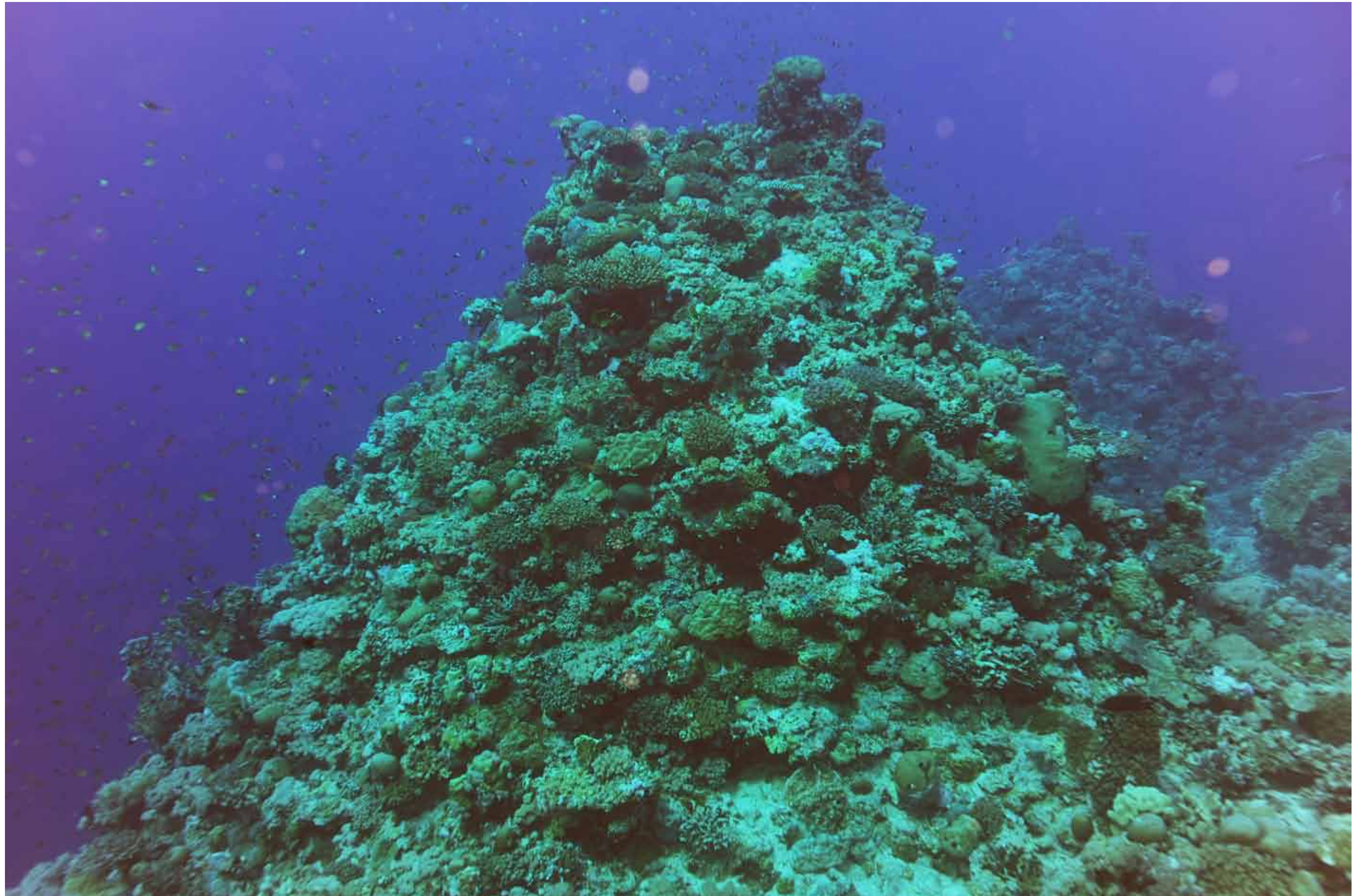


**Farasan Banks Habitats**

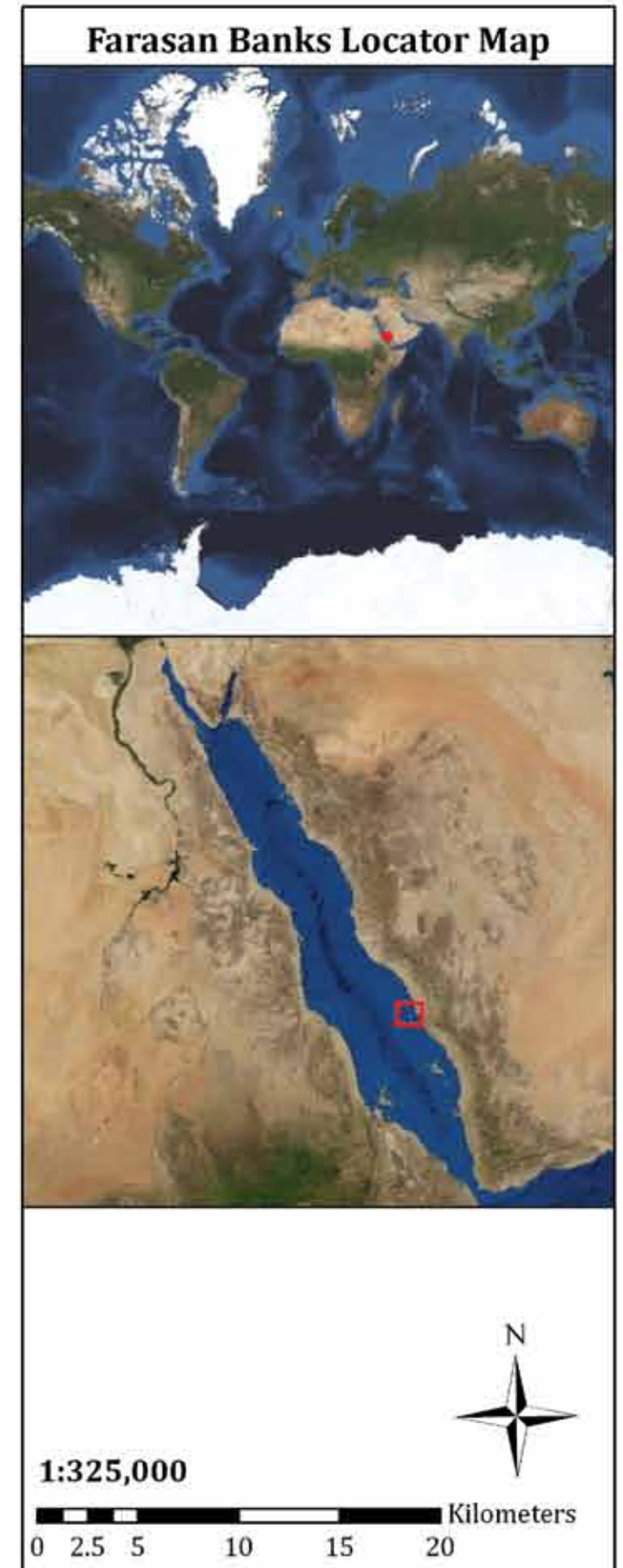
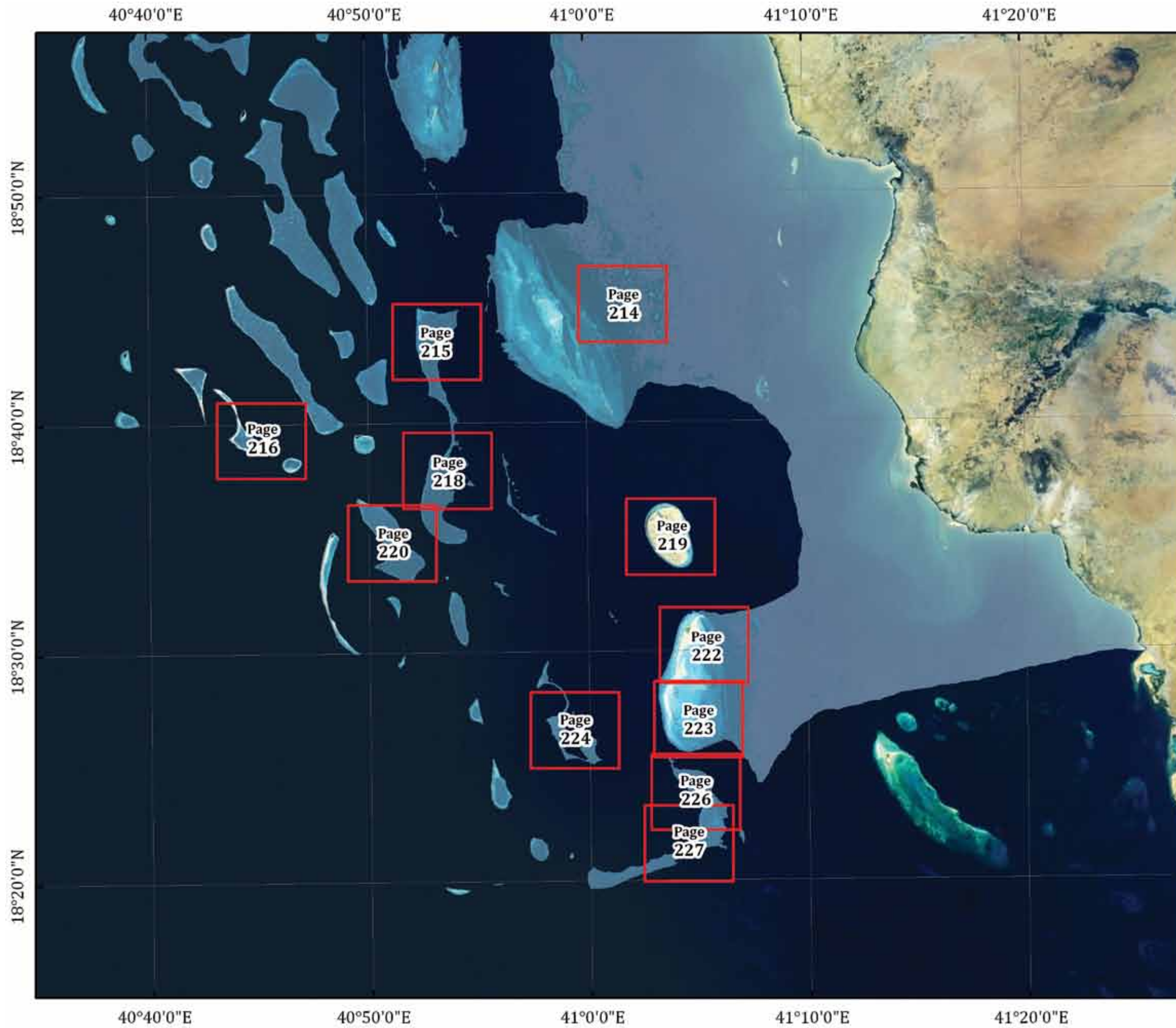
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- Sand and mud flats
- Deep water

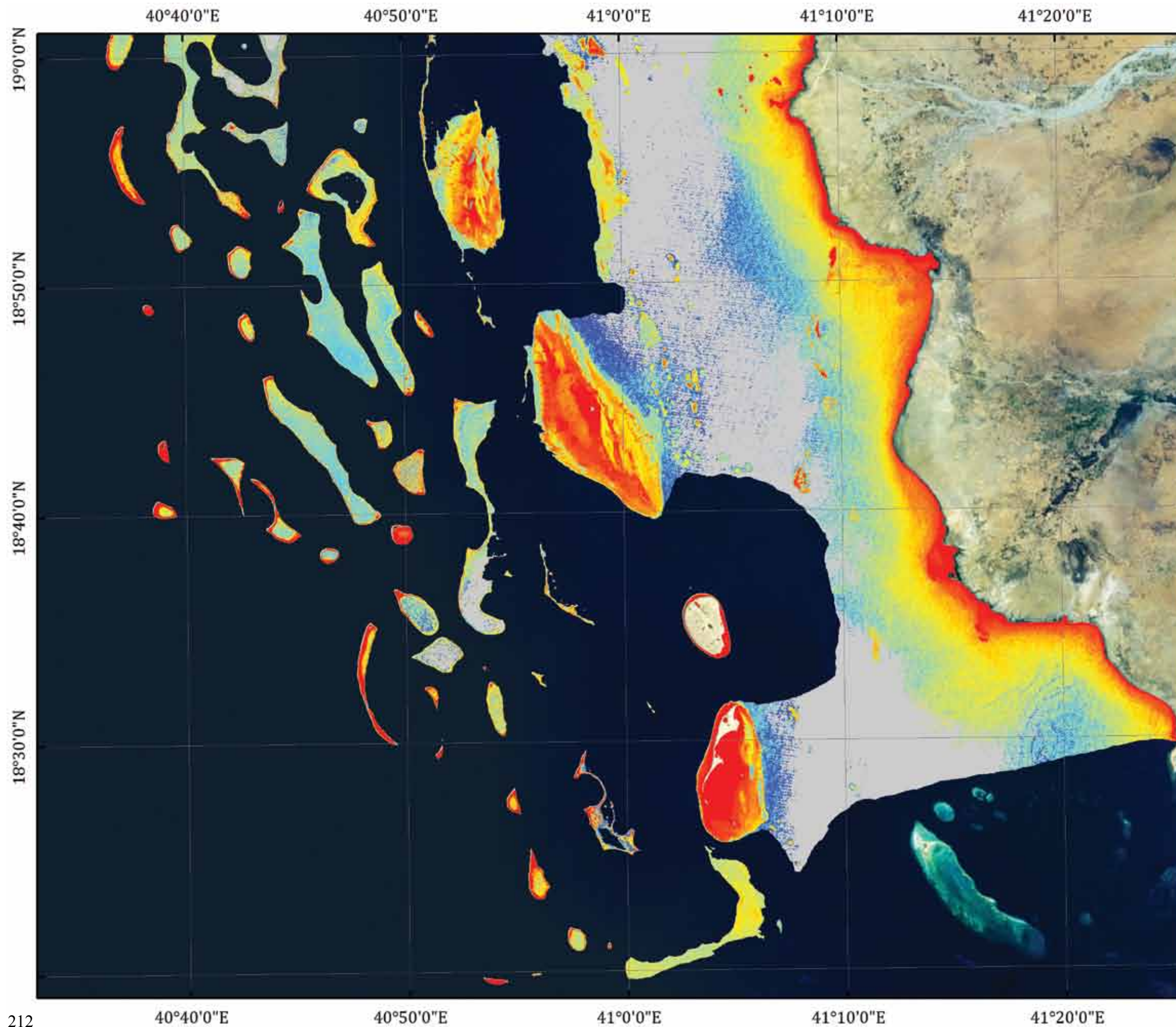
**1:24,000**





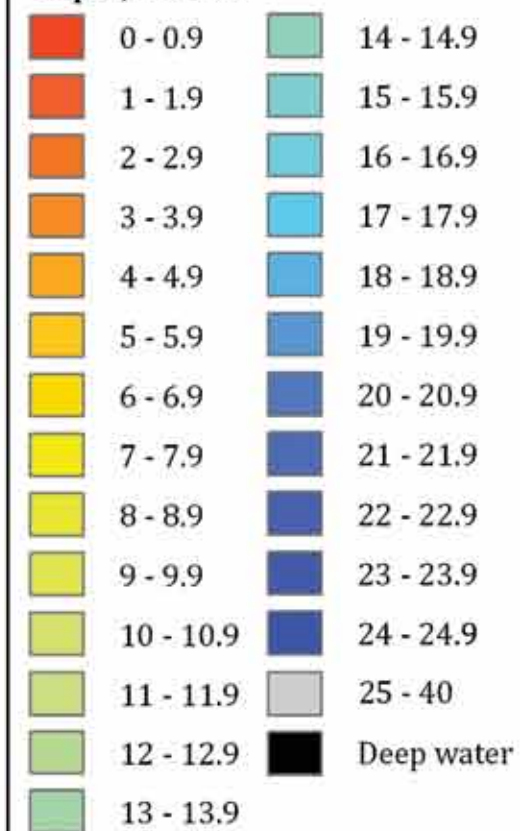
The Farasan Banks are known for their unique and highly variable reef types, including dramatic tower reefs that resemble atolls. Offshore reefs often consist of mountainous pinnacles, like that shown here, extending from the depths up toward the surface. The sides of these structures are steeply sloping and are colonized by diverse coral assemblages.





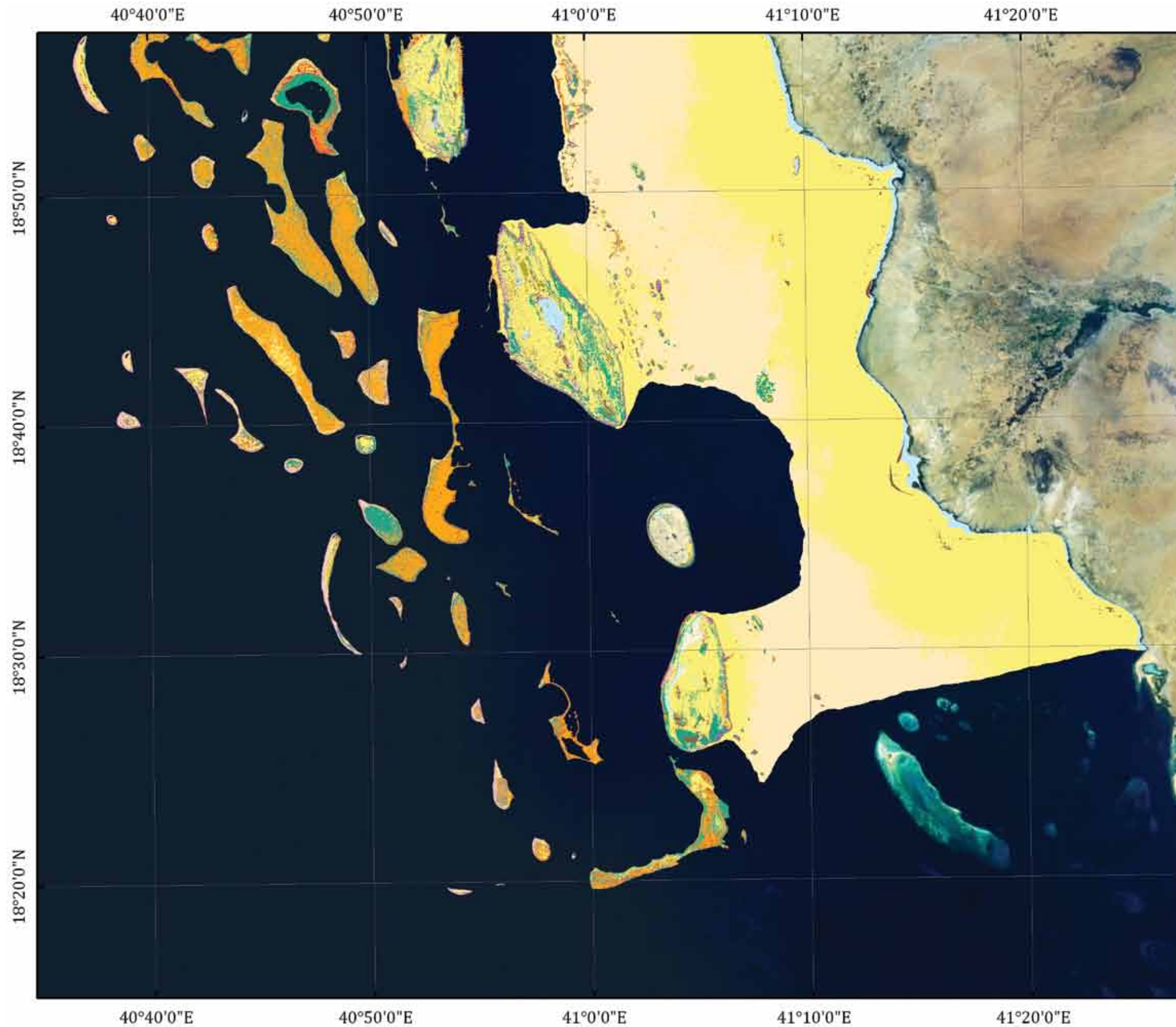
**Farasan Banks Bathymetry**

Depth, meters



1:325,000





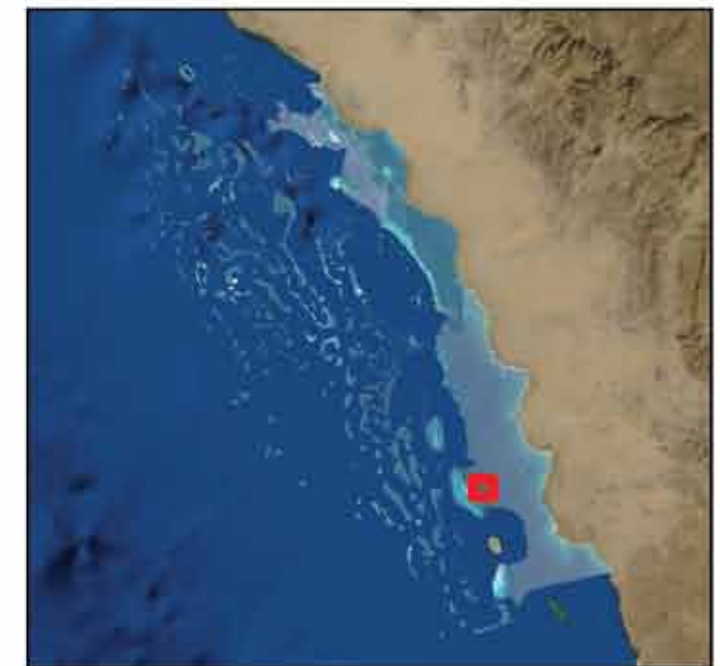
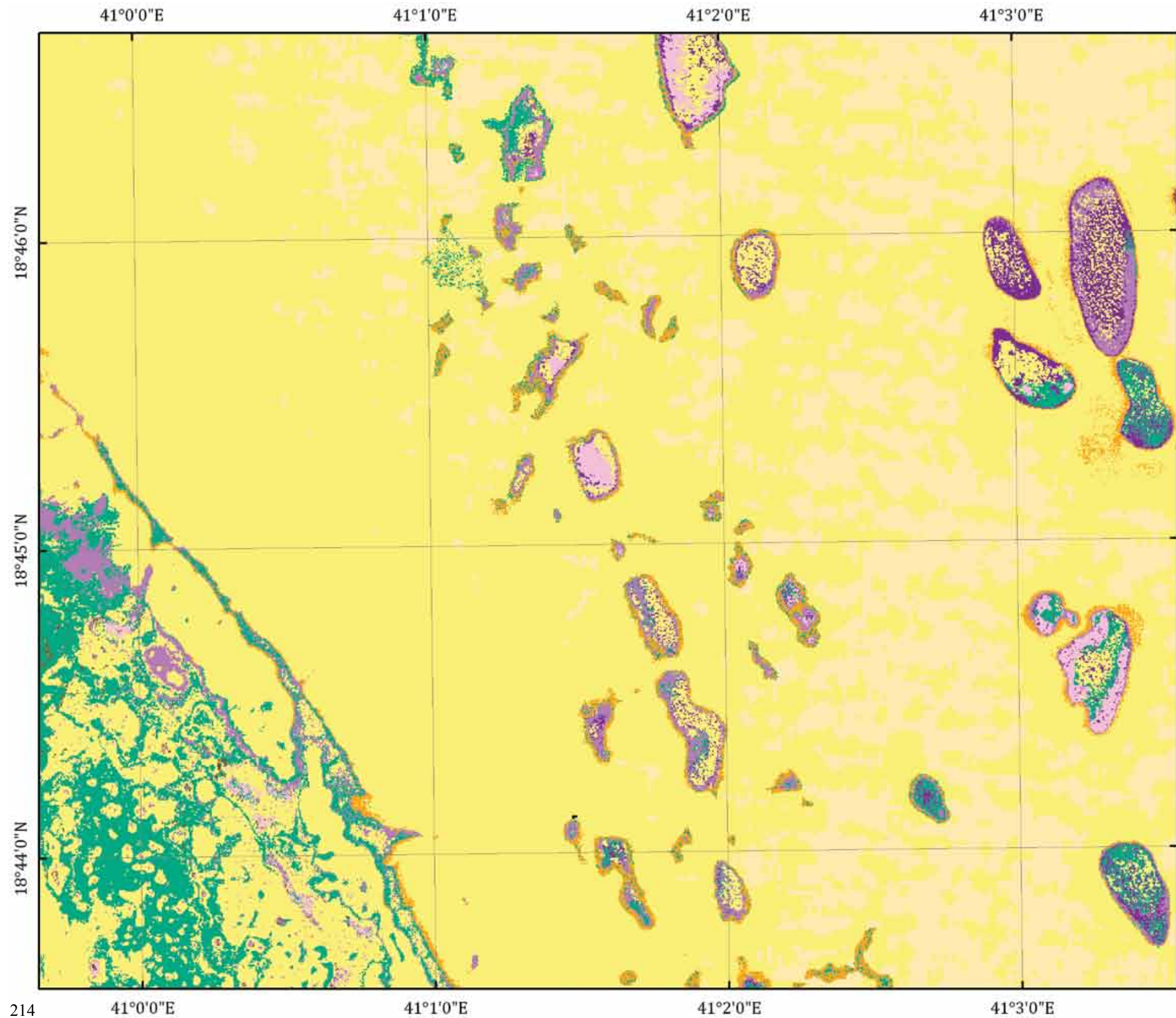
### Farasan Banks Habitats

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Reef walls and drop-offs
- Sparse corals, rubble and sand
- Seagrass meadows
- Macroalgae, sponges, sandy hardgrounds
- Cyanobacteria mats on sand
- Mangroves and near-shore vegetation
- Scoured channels
- Carbonate hardground and reef flats
- Shallow sand sheets
- Deep lagoonal sands
- Sand and mud flats
- Deep water

**1:325,000**

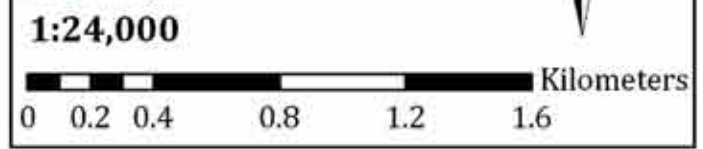


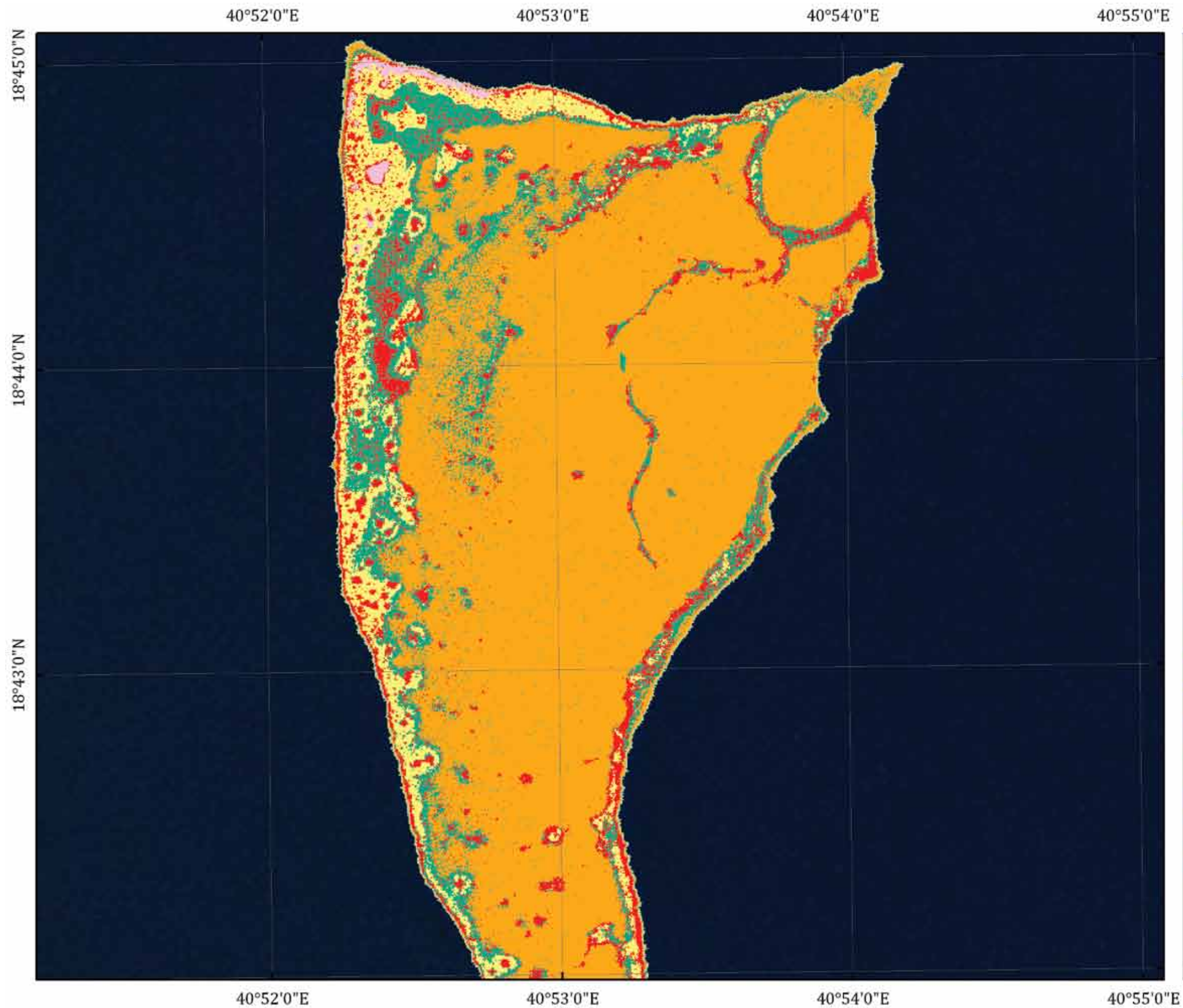
0 2.5 5 10 15 20 Kilometers



**Farasan Banks Habitats**

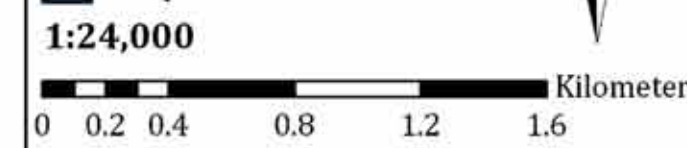
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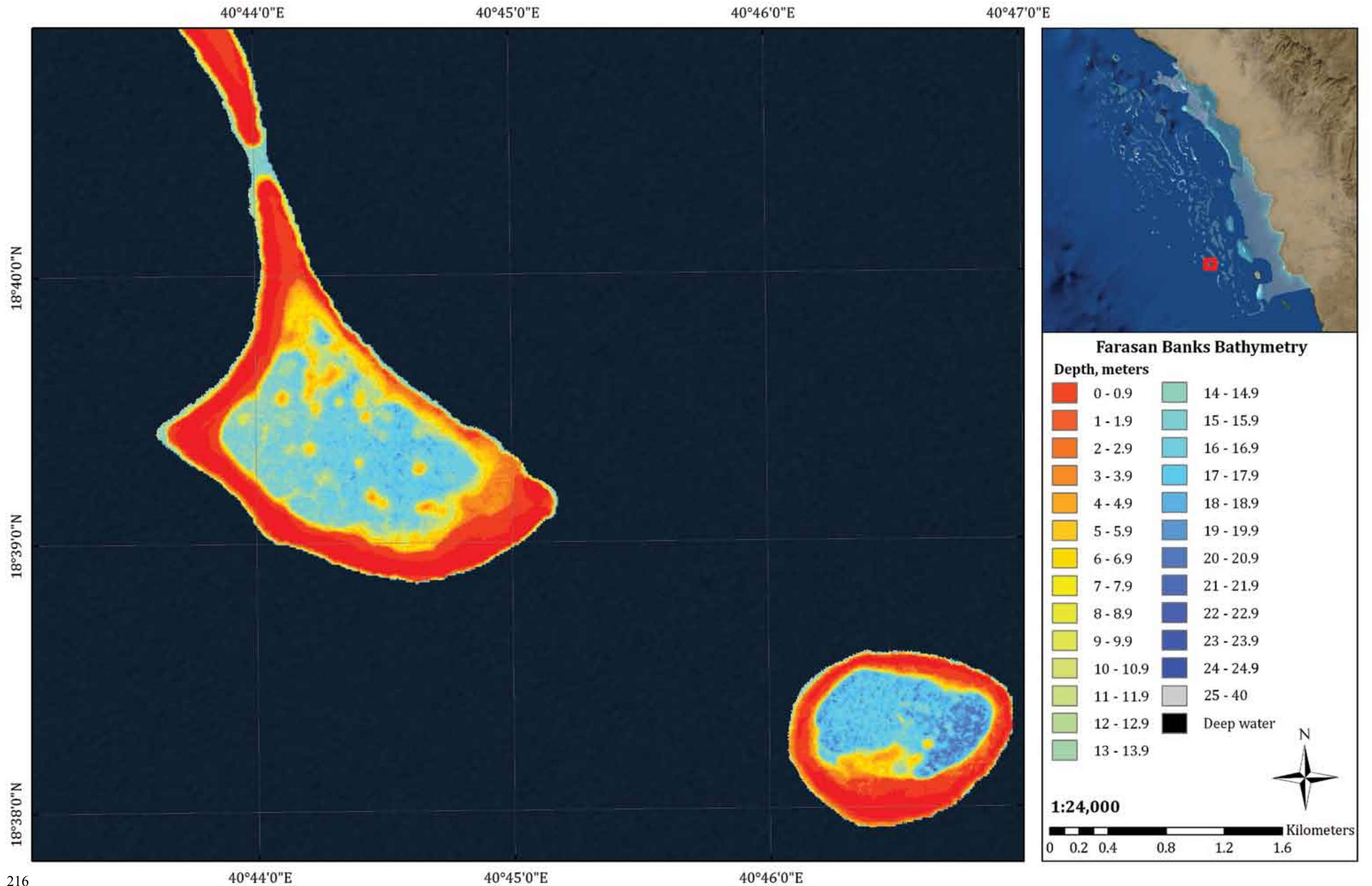


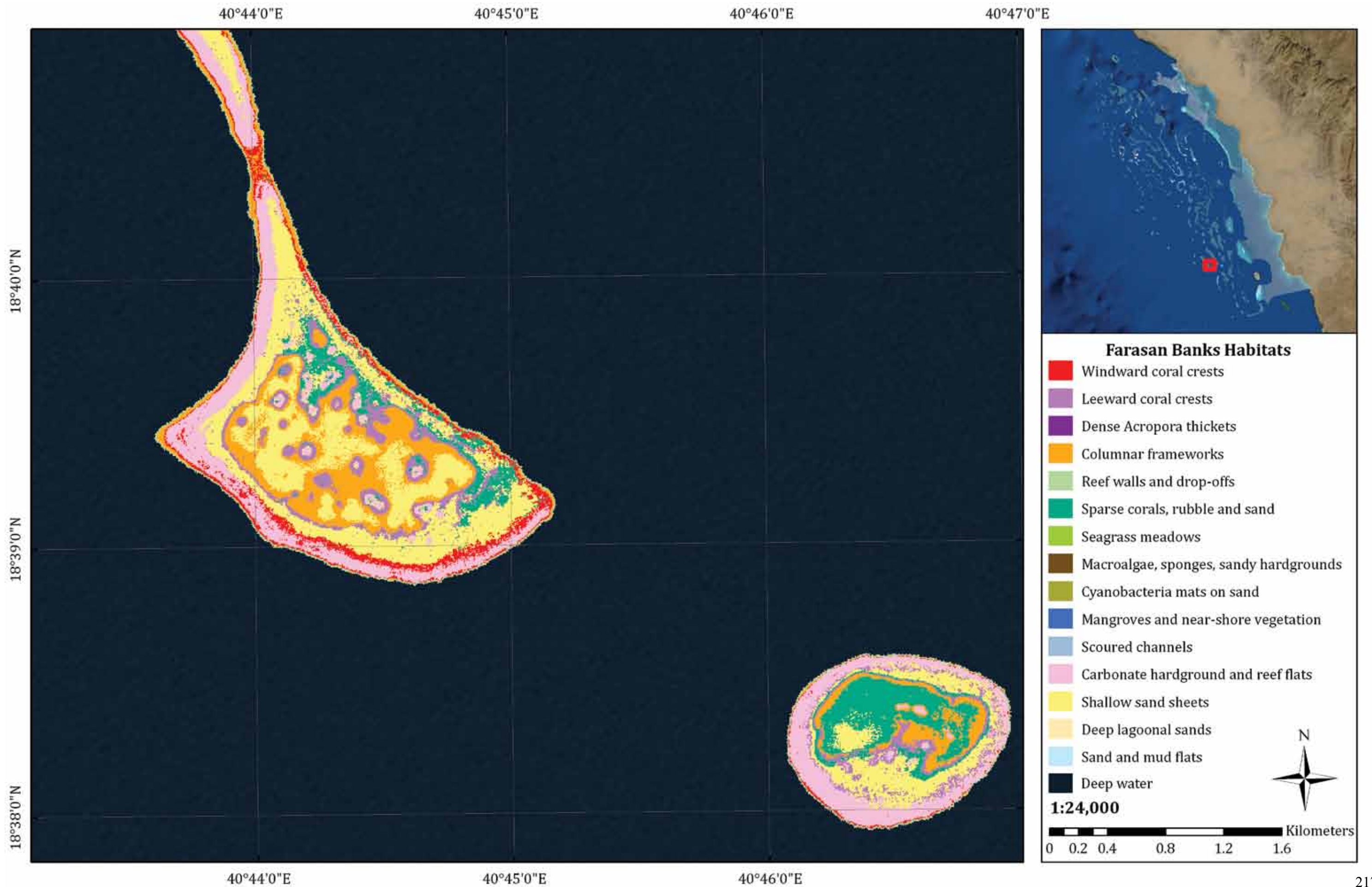
**Farasan Banks Habitats**

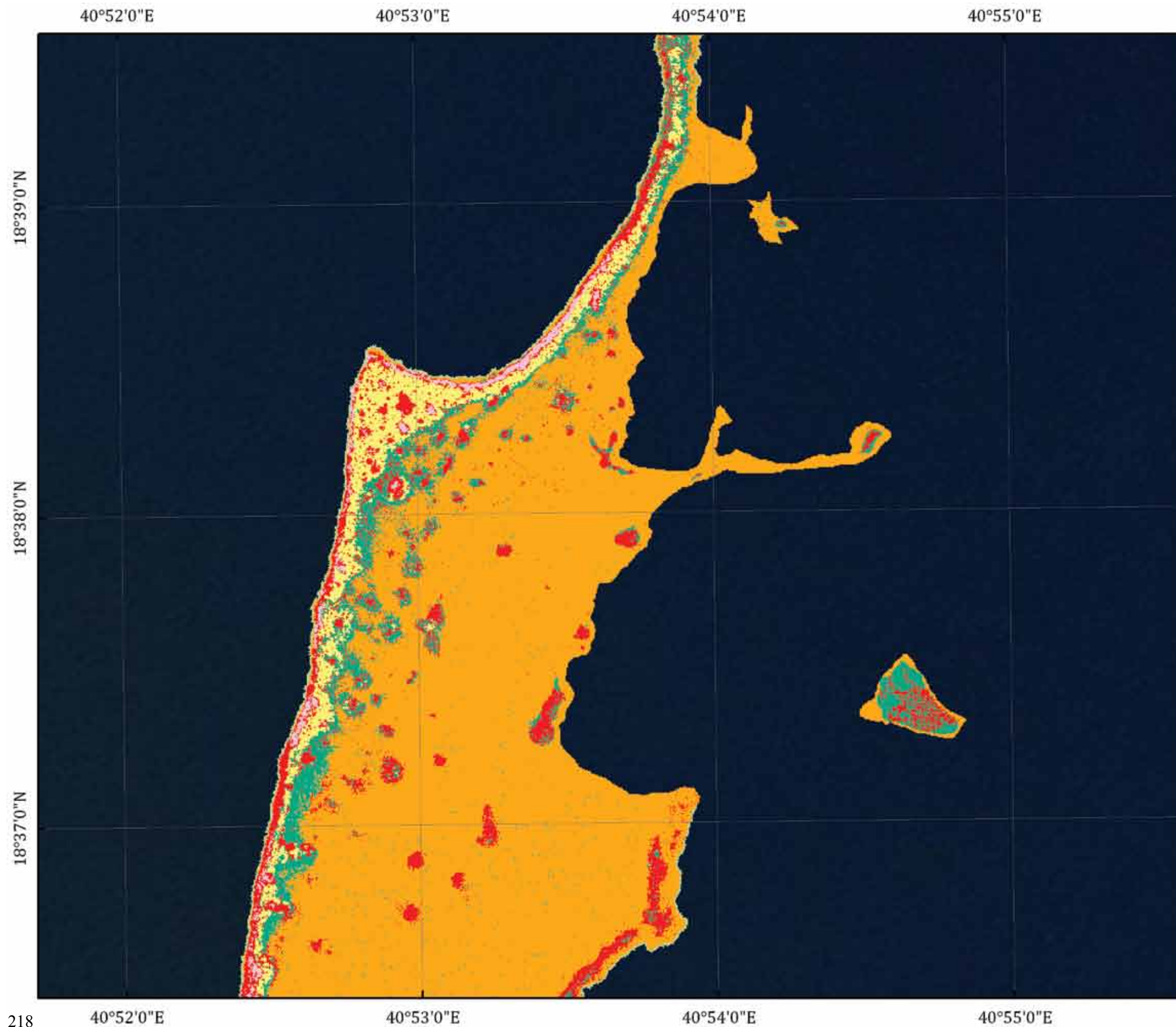
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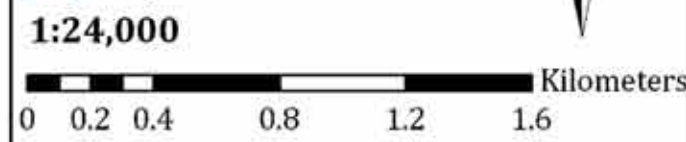


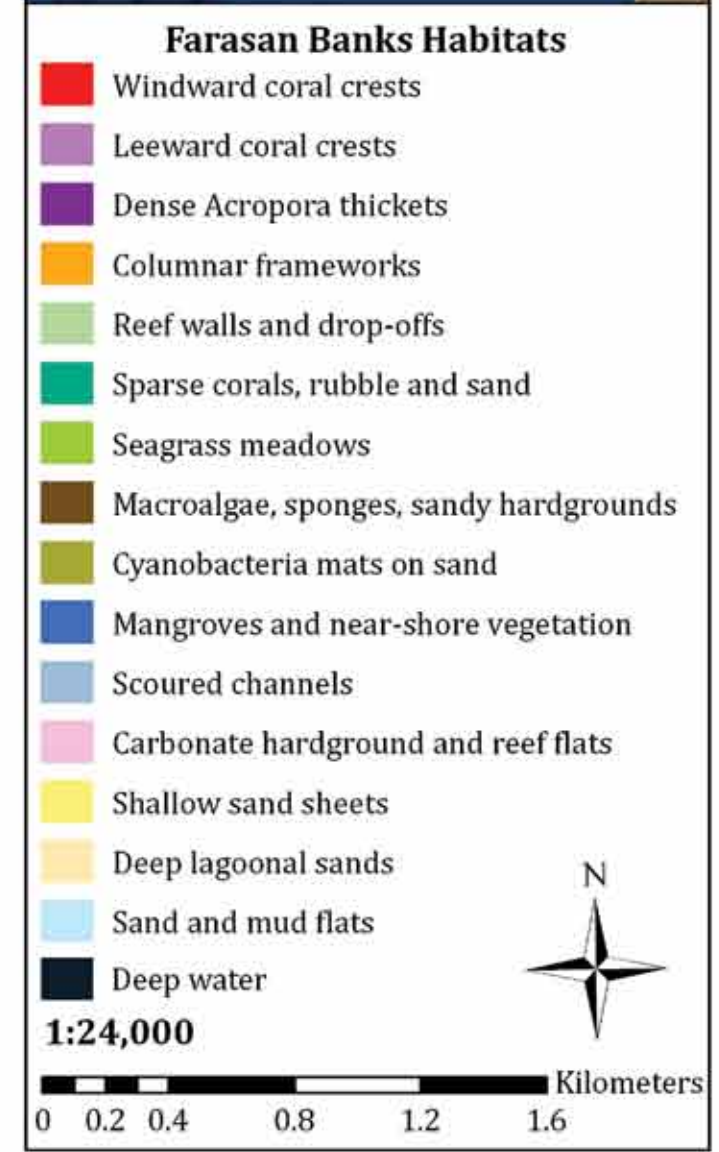
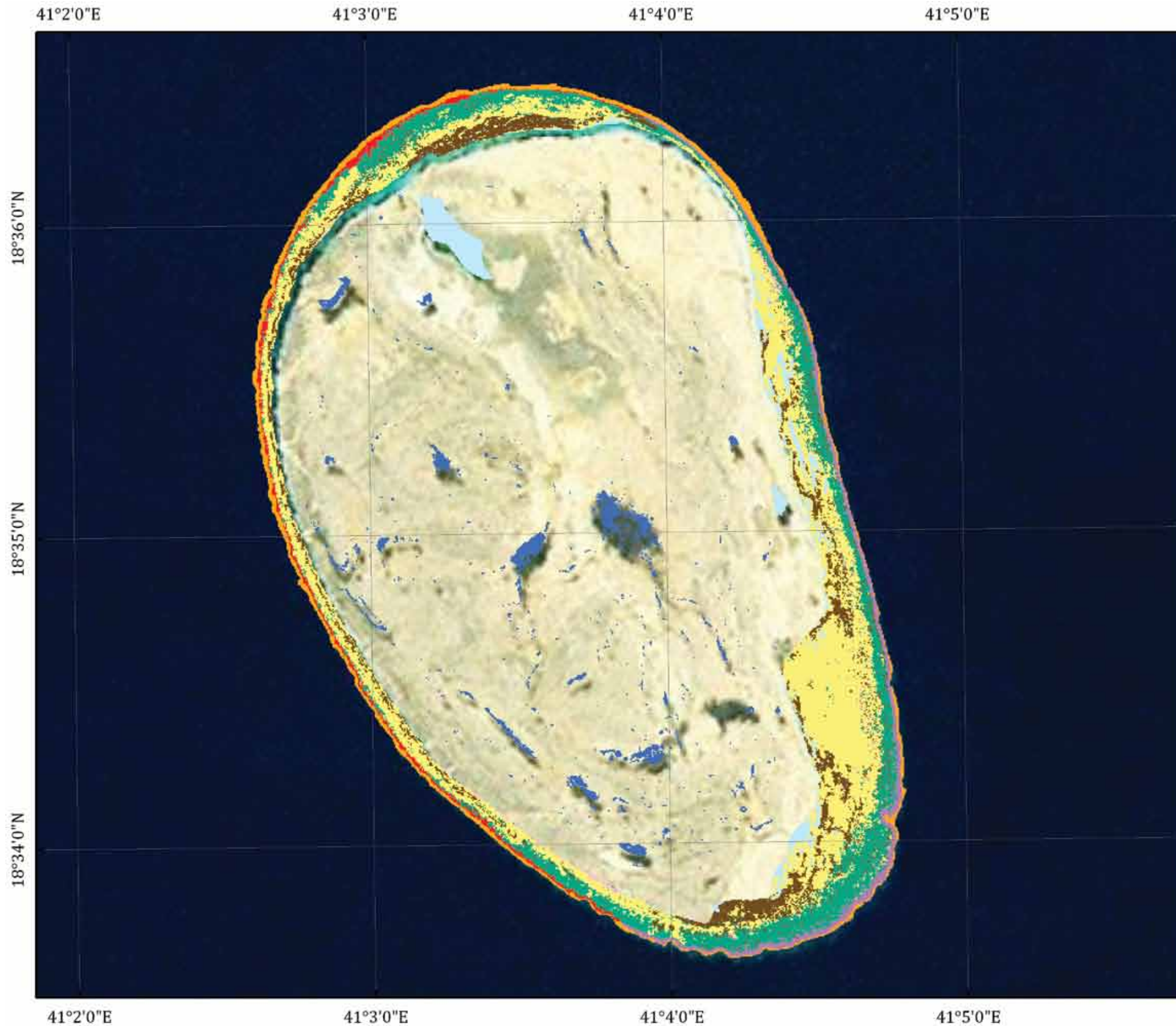


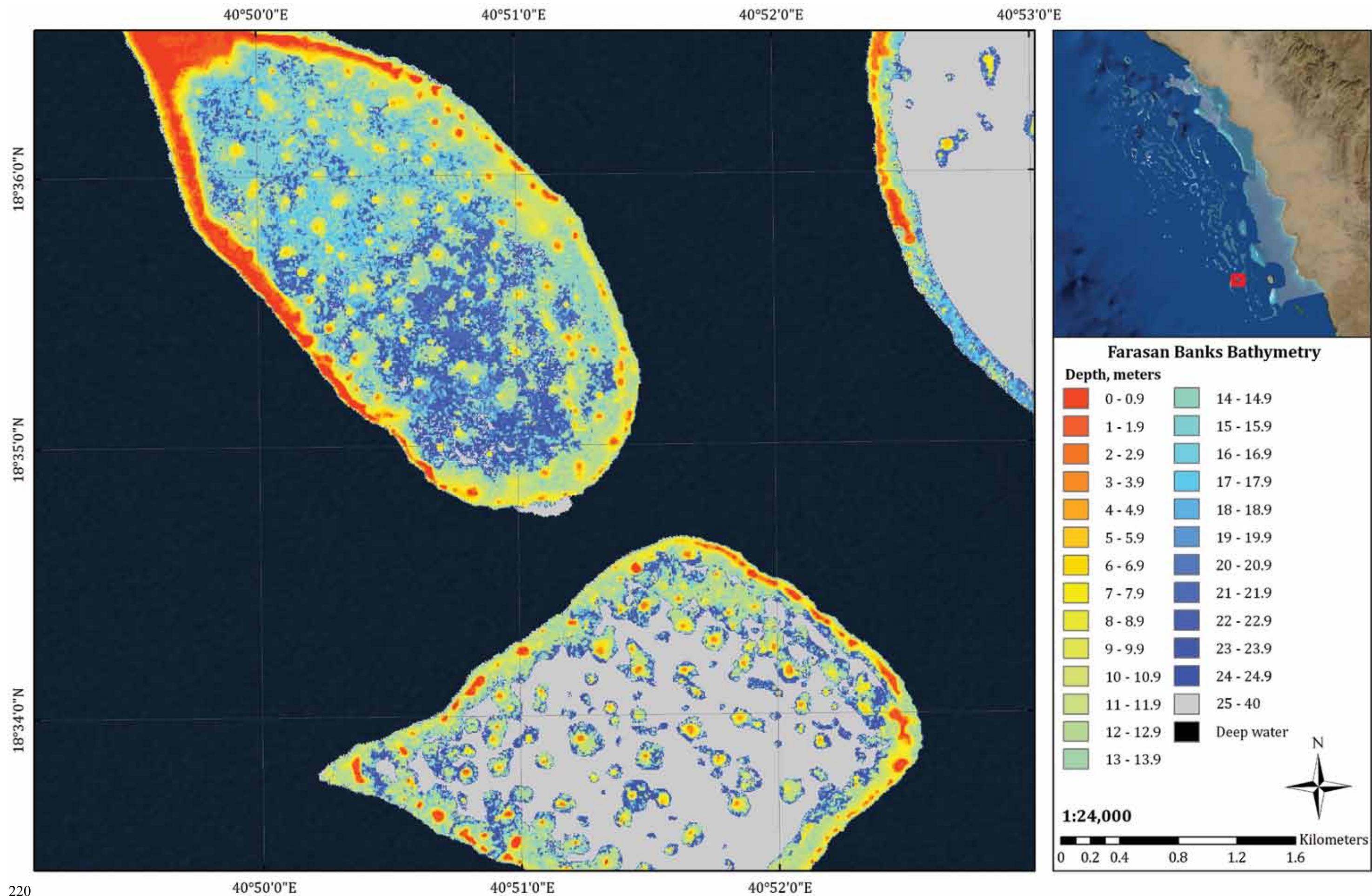


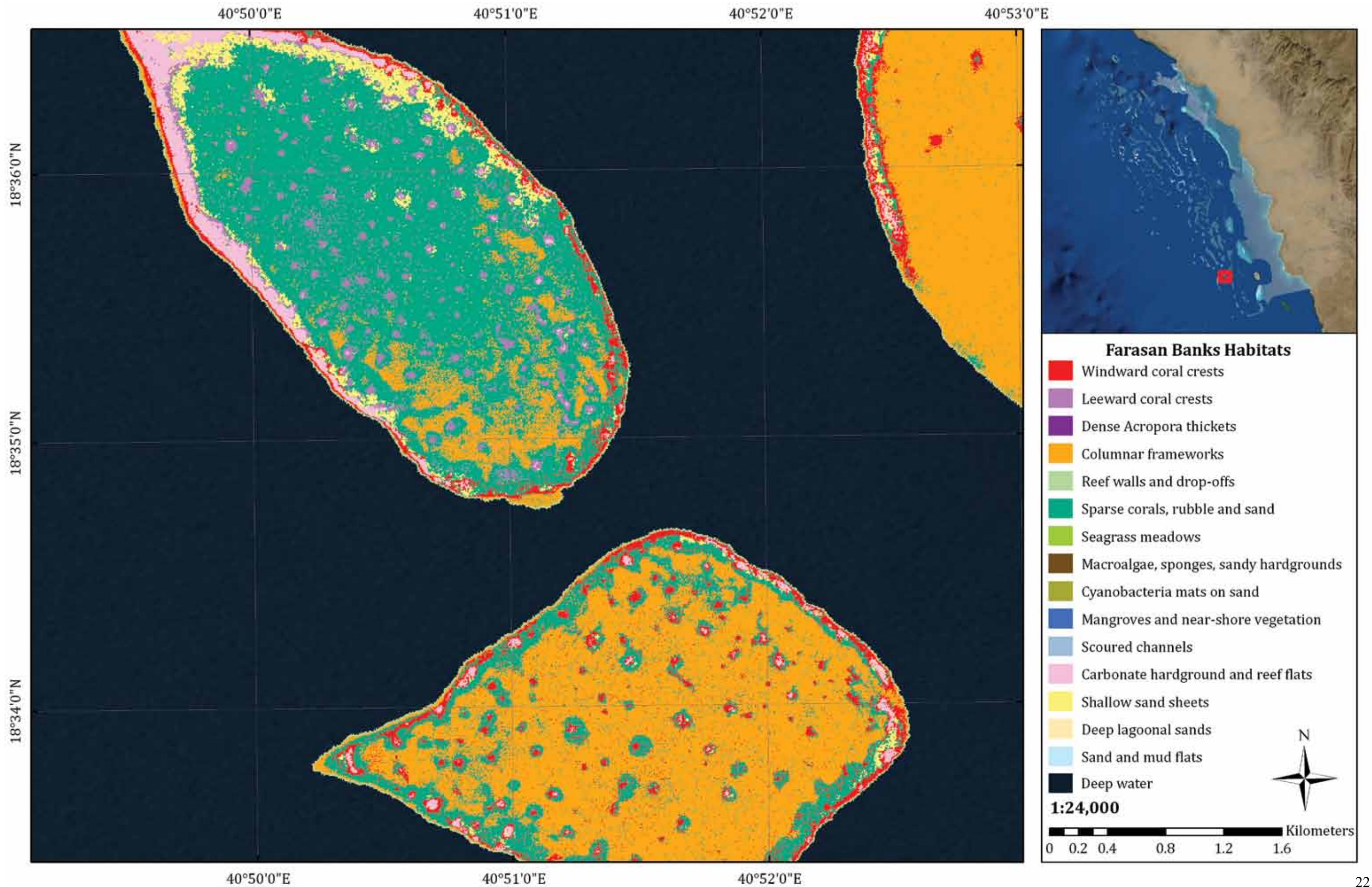
**Farasan Banks Habitats**

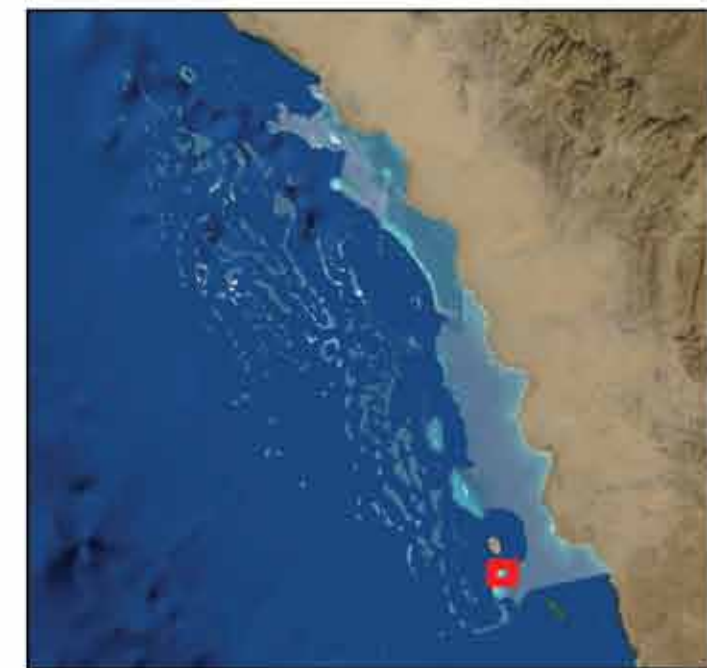
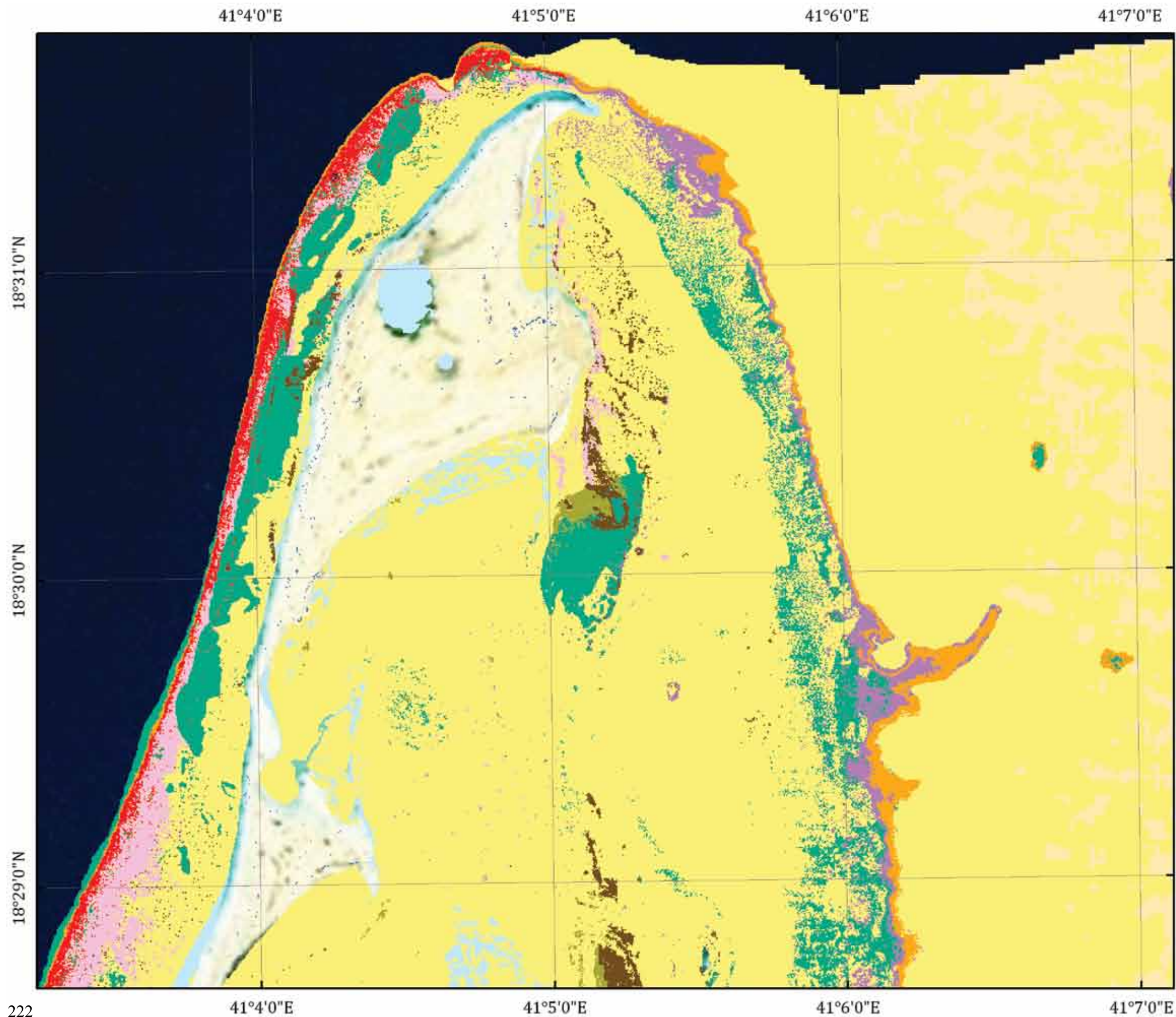
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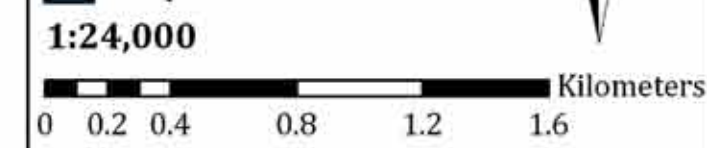


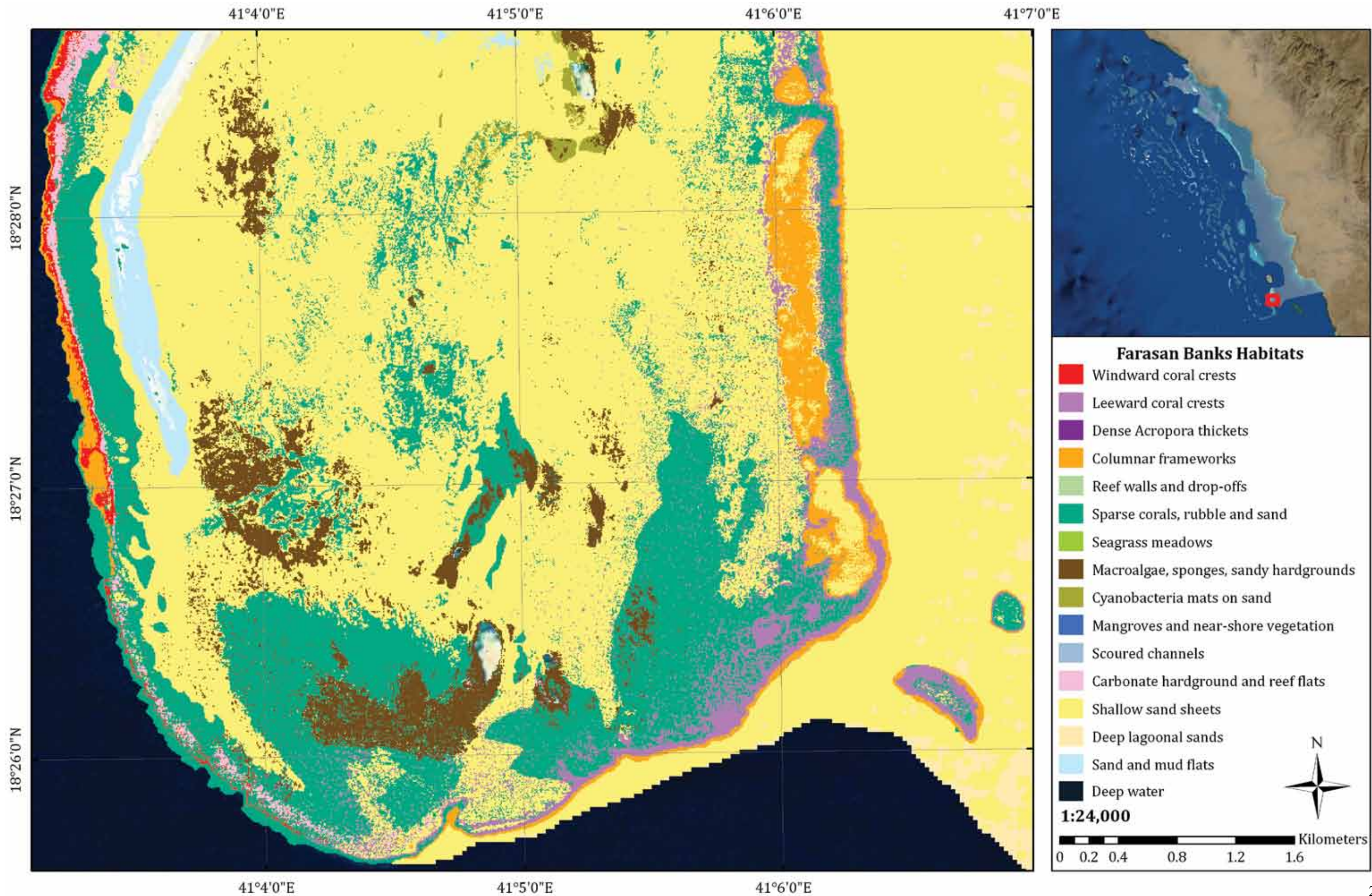




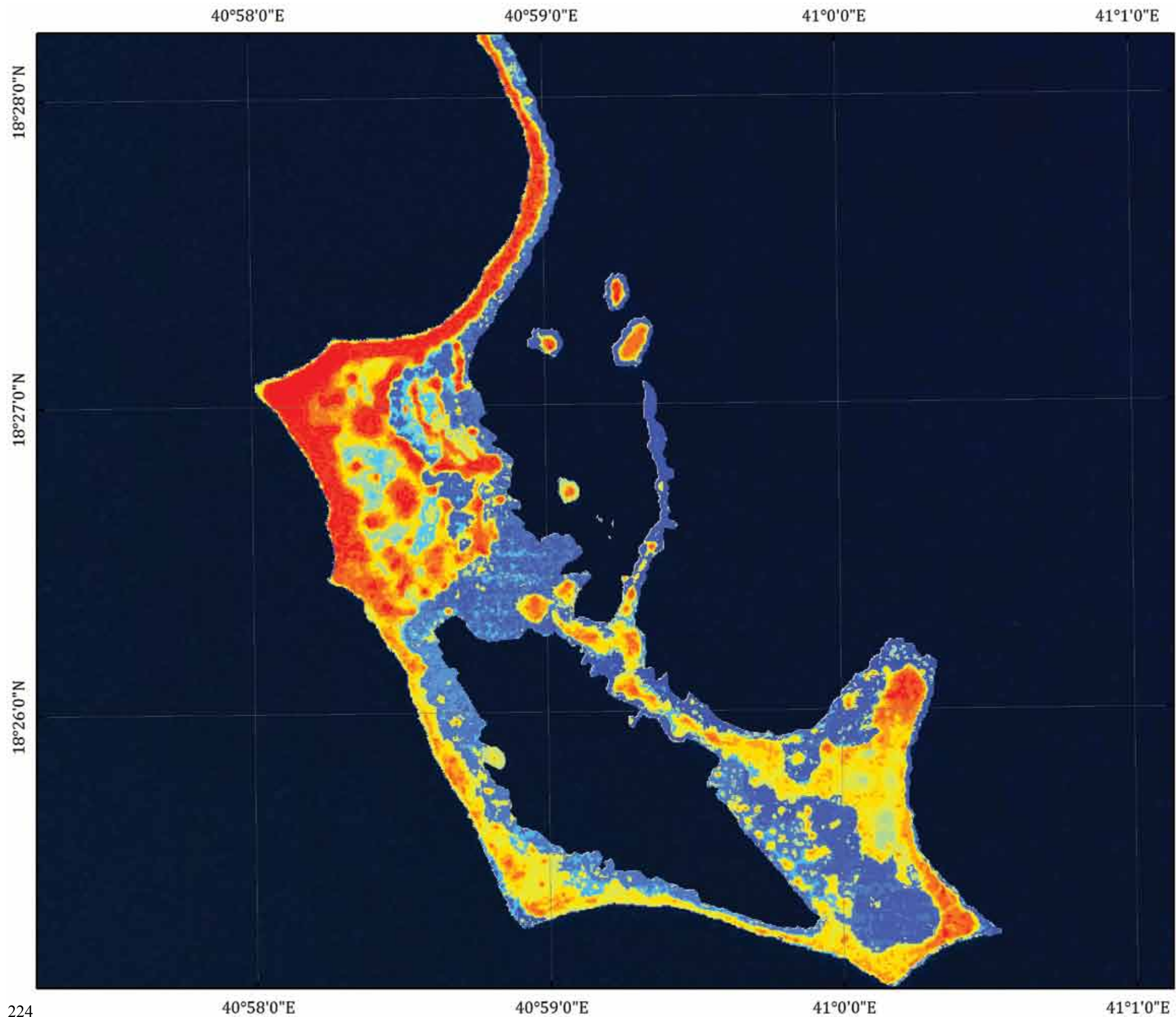
**Farasan Banks Habitats**

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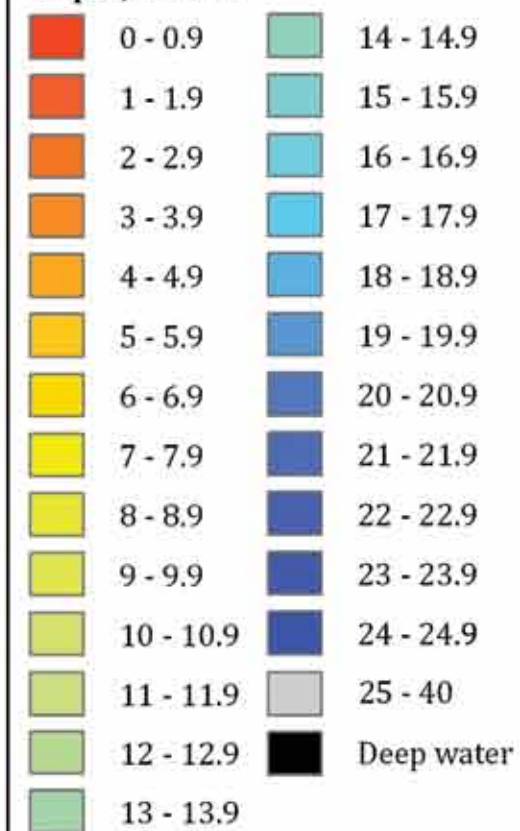




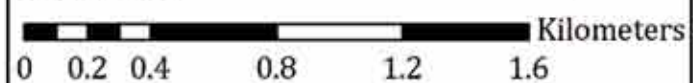


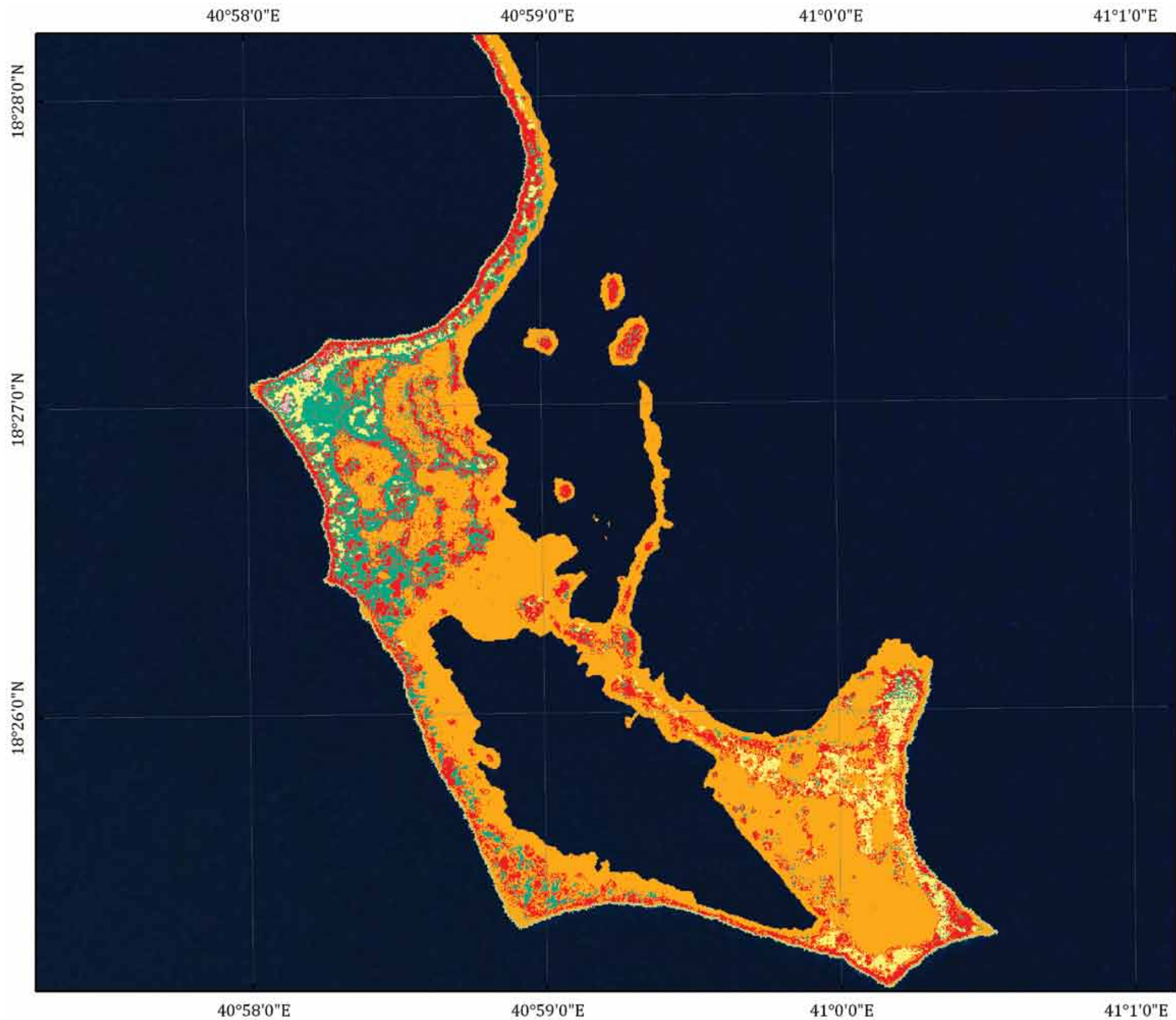
**Farasan Banks Bathymetry**

Depth, meters



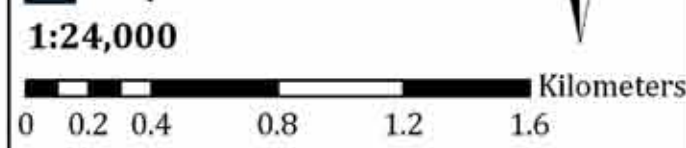
**1:24,000**

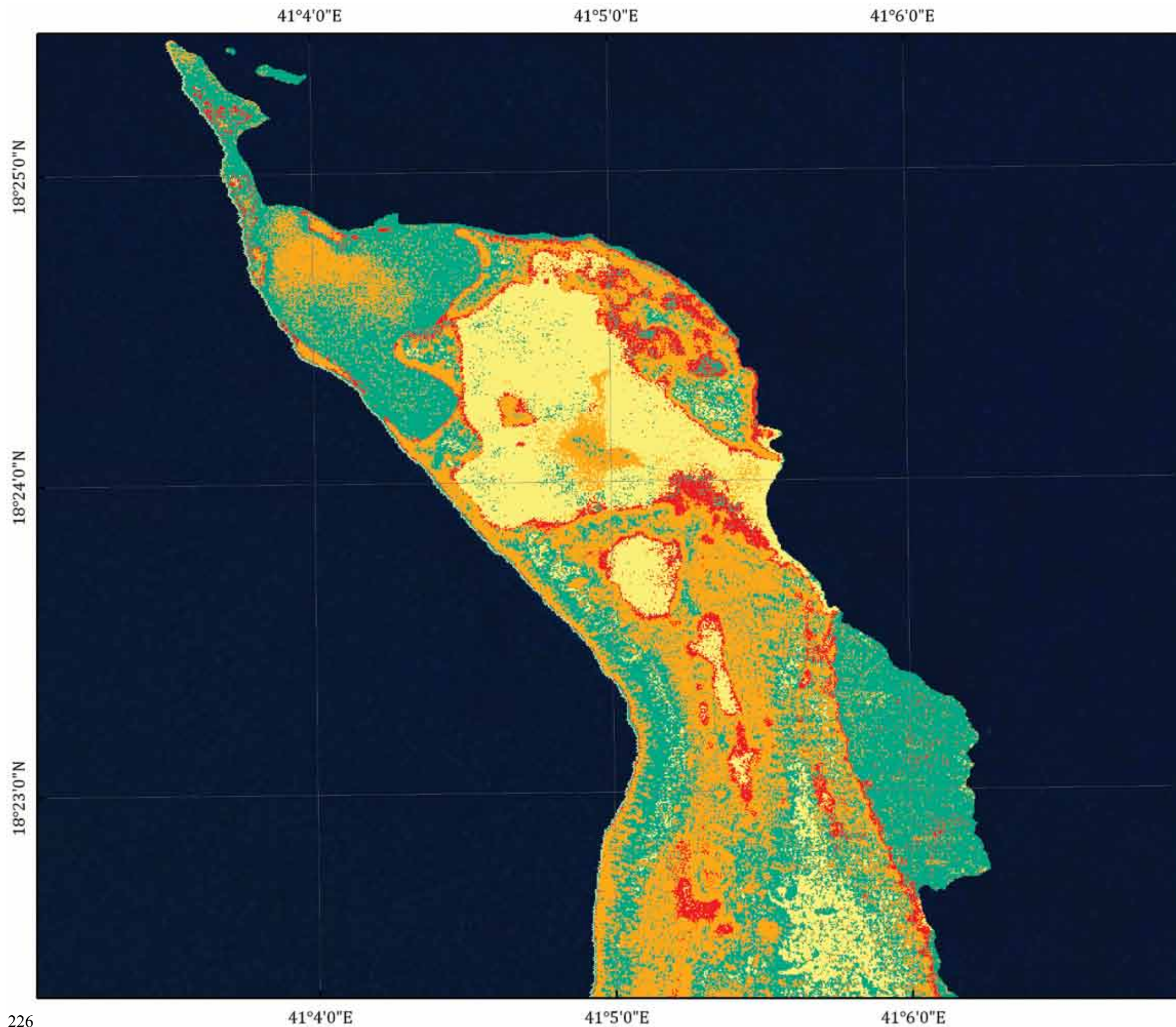




**Farasan Banks Habitats**

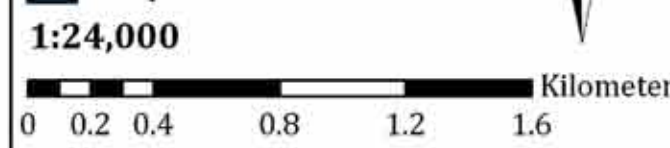
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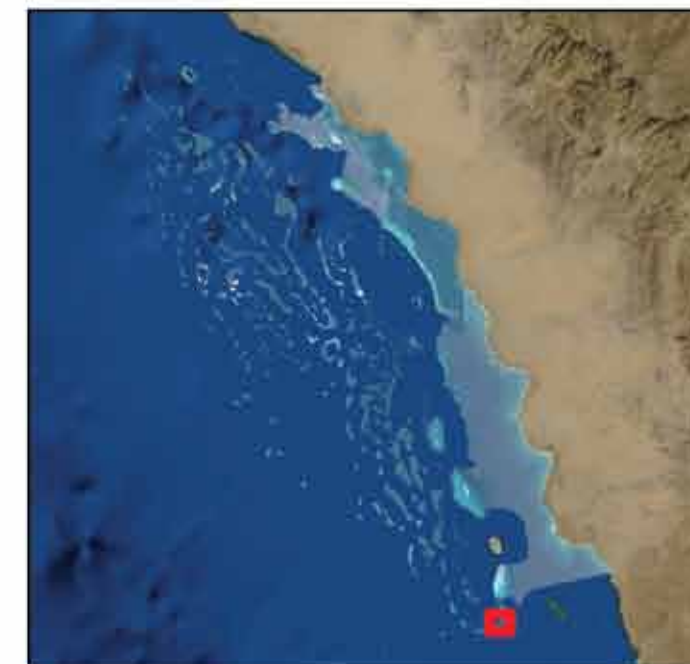
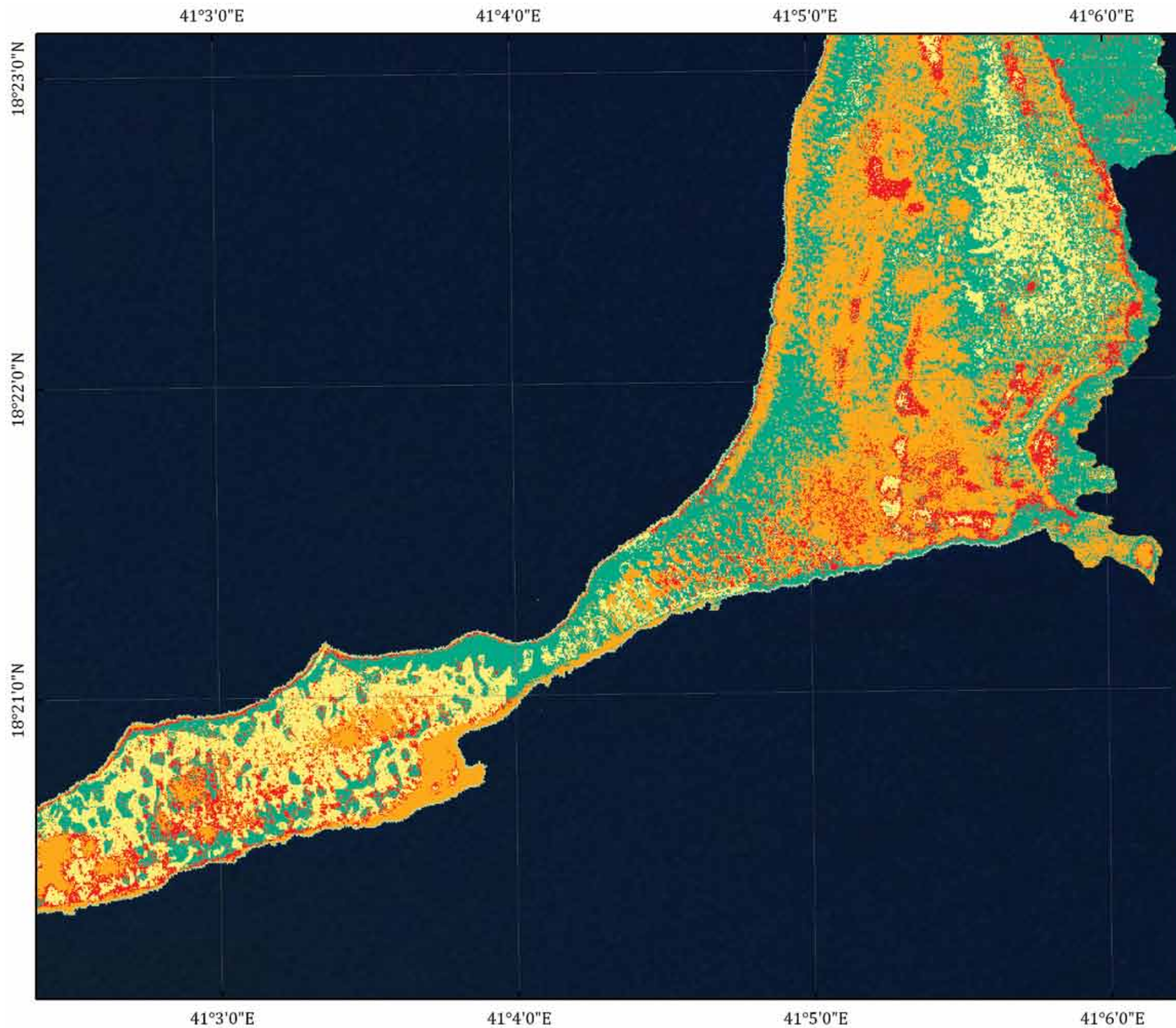




**Farasan Banks Habitats**

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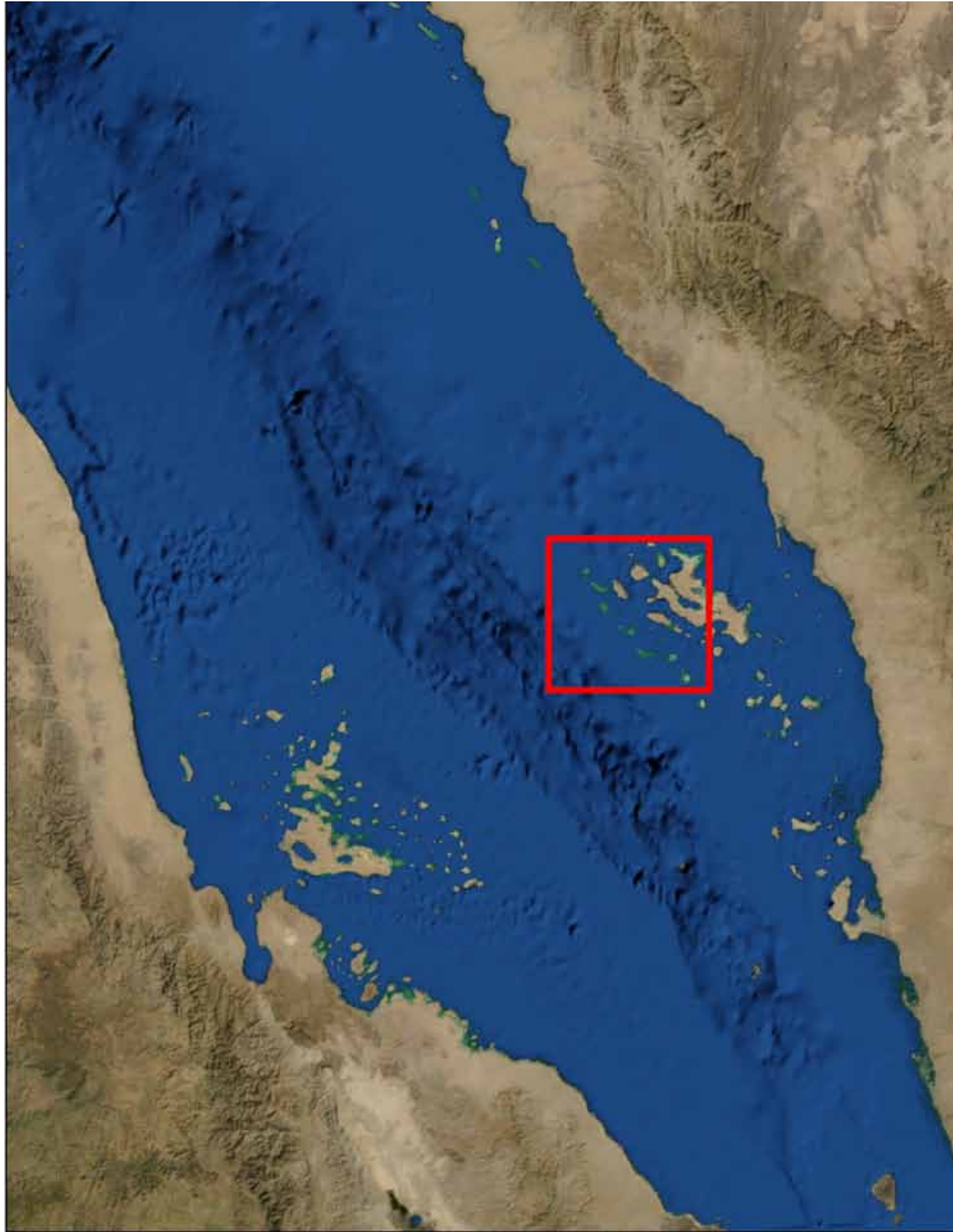


**Farasan Banks Habitats**

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**1:24,000**





# Farasan Islands



## The Farasan Islands

The Farasan Islands are situated in the southcentral Red Sea at 16°20'–17°20'N, 41°24'–42°26'E, approximately 40 km from the coastal town of Jizan, Saudi Arabia. The Farasan Islands lie on the Arabian continental shelf, which is less than 200 m deep and about 120 km wide at Jizan. The archipelago contains approximately 176 islands. Most islands are low, and composed mostly of pavements and faulted blocks of uplifted fossil reef limestone. Together, they form five irregular, northwest-trending lines (ridges) of raised coral reefs, coral pavements, and shoals. These were formed in Tertiary seas and raised up by a salt dome or diapir, the product of intense evaporation when the Red Sea was cut off from the Indian Ocean.

The largest island in the region is Farasan Kabir. Farasan Kabir is 66 km long and 2–8 km wide, with a total area of 381 sq km and a 216 km coastline. This island contains rocky ravines and low ridges north and east of Farasan town and at the western end of the island. The main ridge is 30–40 m high and is fissured with gullies and low cliffs. It divides into parallel hills and valleys beyond Syar, rises to 72 m in Jabal Buttan south of Syar, and ends in 20 m cliffs above al-Hussain harbor. Farasan Kabir is connected to Sajid Island by a bridge. As-Saqid Island is 27 km long and 149 sq km in area and is largely flat with a higher western end. The smaller islands of Ad Dissan (35.7 sq km), Zufaf (33.2 sq km), and Sasu (19.7 sq km) are located 5–15 km west and southwest of Farasan Kabir. On the mainland side of these islands, the coastline is tilted upward approximately 50 m above sea level. Qummah (15.2 sq km) and Domsok (12 sq km) lie south of Janabah Bay. There are also 23 smaller islands (>0.2 sq km area) and over a hundred other low islets and shoals. Nearly half of these are rocky, including the chain from Dumsuq to Sarad Sarso; the Galam Islands in the southeast; and Wiska, Jabal Mohammad and West Manzhar islands in the northeast. About a third of these smaller islands are sandy; 20% have both rocky and sandy areas. Most of the islands are surrounded by narrow bands of reefal habitats, generally with water depths of less than 11 m.



Pleistocene rocks cropping out at a sea cliff in the Farasan islands.

About 60% of the surface of the Farasan Islands is a subtropical desert of fossil limestone. It is flat and well drained, with high humidity and low annual rainfall (<50 mm) and constant winds. The remainder is divided approximately equally among silty sand and sabkha, and rocky outcrops between 10 to 70 m high. Above the intertidal zone, beaches usually have a band of *Suaeda monoica*, *Halopeplis perfoliata*, *Limonium axillare*, and several species of *Zygophyllum*. Inland, vegetation cover is sparse, except in gullies between fossil coral outcrops. Sheltered coastal areas support extensive stands of *Avicennia marina* mangroves. Northeast Farasan Kabir supports the largest patch of *Rhizophora mucronata* known to occur in the Saudi Arabian Red Sea. The Farasan Islands exhibit different biophysical and geomorphological characters when compared to the northern Red Sea. Most of the benthic species found here are better suited to turbid, sediment-loaded waters, which predominate in this area due to terrigenous input and water mixing across the wide shallow coastal shelf. The highest Sea temperatures are also found in the Farasan Islands, and coral development is restricted largely to offshore sites. In addition to mangroves, other shallow marine habitats include seagrass beds, coral-dominated fringing and patch reefs, algae-dominated fringing and patch reefs, coral-algal fringing reefs, platform reefs, pavement, shoals, mud flats, and subtidal sand expanses.



**Above:** Aerial photograph of a small, offshore island. Extensive sandy beaches occur off the north and west, while mangrove development occurs on the eastern side. The island is surrounded by extensive reef habitat. Circular islands and gentle morphology suggest subsurface salt was a driving factor in generating this island.

**Opposite page, left:** Location of the Farasan Islands. Source of basemaps: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

**Opposite page, top right:** The gentler morphology in the Farasan Islands is determined by salt tectonism. Salt domes push towards the surface, creating the topographic highs of islands and reefs.

**Opposite page, bottom right:** Extensional dynamics of the Red Sea have created a series of normal faults that determine much of the shape and morphology of Red Sea islands and reefs.



**On top of the wide, shallow banks that surround the Farasan Islands, many circular patch reefs are found.**



**The soft coral *Dendronephthya* forms dense aggregations on offshore reefs.**



**Dense *Acropora* thickets dominated by branching and plating colonies exist on the offshore reefs at the northwestern end of the submerged bank system.**



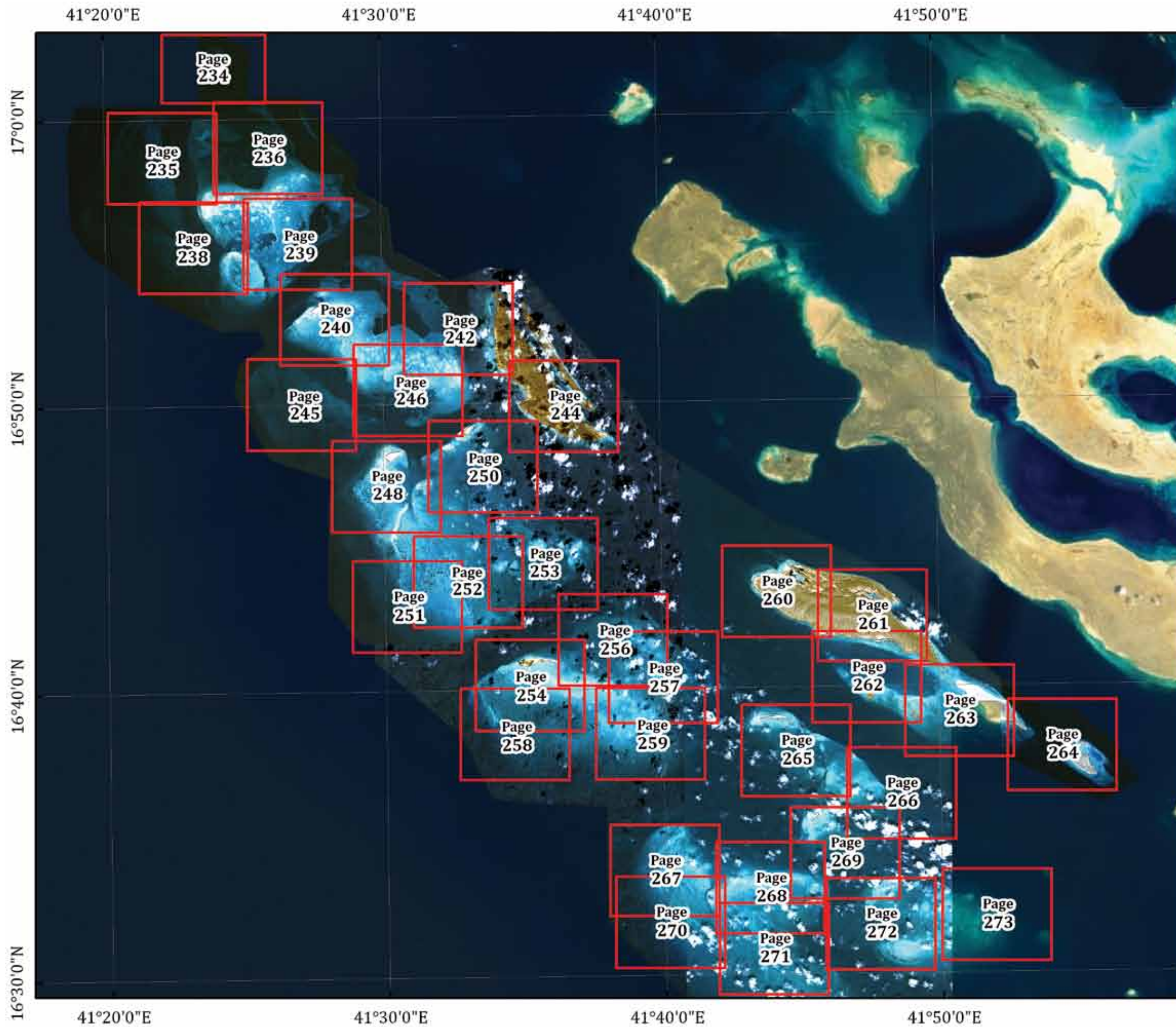
## Farasan Islands Imagery and Habitat Maps

Farasan Islands habitat mapping focused on shallow, offshore habitats, seaward (to the west and northwest) of the main islands. This region was mapped using a combination of QuickBird multispectral satellite imagery and AISA *Eagle* hyperspectral imagery acquired using the *Goldeneye* Seaplane. The project was supplemented with more detailed hyperspectral imagery because the satellite imagery had considerable cloud cover, as depicted in several of the 1:24,000 scale bathymetric maps and in the locator maps for each of the 1:24,000 habitat maps.

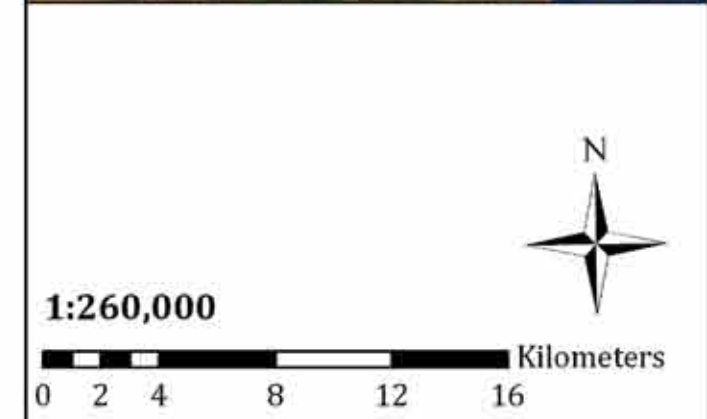
Satellite imagery, bathymetry, and habitat maps for the Farasan Islands are illustrated on pages 230-273. QuickBird multispectral satellite imagery of the Farasan Islands (left), locator map (page 231), bathymetry (page 232), and a resulting habitat map for the same area (page 233) are shown at a scale of 1:260,000. Higher resolution habitat maps (1:24,000) and bathymetric maps for representative areas within the Farasan Islands are shown on subsequent pages. Each of the six 1:24,000 scale bathymetric maps included in this section are on the left (even-numbered) page and the habitat map for the same area is shown on the right (odd-numbered) page. Habitat maps start in the northwest and work progressively southward. These include habitats associated with the barrier reef, lagoonal environments, and nearshore habitats. Source of terrestrial basemap imagery used in all habitat maps and bathymetric maps is: ESRI, i-cubed, USFSA, USGS, AEX, GeoEye, AeroGRID, Getmapping, IGP.

A total of 742 sq km of shallow offshore habitats was mapped and subdivided into 12 habitat classes with areas below 25 m depth (deep water) depicted in dark blue. The most extensive habitat types were shallow sand sheets, which made up nearly 60% of all shallow marine habitats in these offshore locations. Corals were found in five habitat types, covering an area of about 80 sq km. Hardground reef flat areas constitute an additional 26 sq km of the bank, while other soft-bottom habitats, with seagrass, algae, and cyanobacteria, occupied 13 sq km. Submerged marine habitats adjacent to emergent islands included some coral habitats, isolated patches of mangroves, shallow sand and mud flats, and algal areas, making up about 130 sq km.

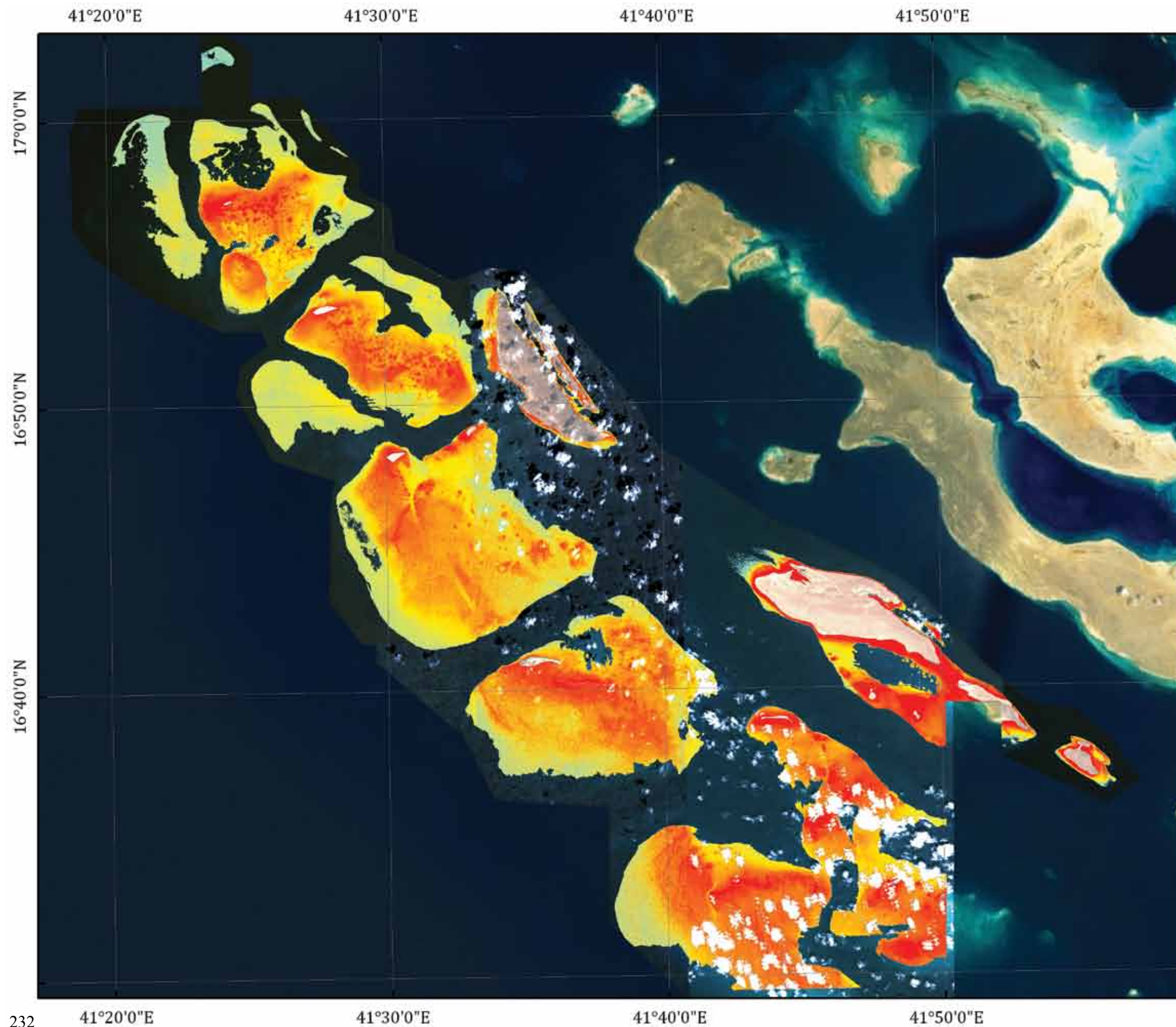
Farasan Islands Habitats	Total area (sq km)	% region total
Reef walls and drop-offs	0.00	0.00
Windward coral crests	7.72	1.00
Leeward coral crests	7.02	0.90
Dense <i>Acropora</i> thickets	23.25	3.10
Columnar frameworks	1.46	0.20
Sparse corals, rubble, and sand	41.37	5.60
Seagrass meadows	10.21	1.40
Macroalgae, sponges, sandy hardgrounds	136.98	18.50
Cyanobacteria mats on sand	8.03	1.10
Mangroves and nearshore vegetation	0.25	0.05
Scoured channels	0.00	0.00
Carbonate hardground and reef flats	26.22	3.50
Shallow sand sheets	443.75	59.80
Deep lagoonal sands	0.00	0.00
Sand and mud flats	35.88	4.80
<b>TOTAL AREA MAPPED</b>	<b>742.14</b>	<b>100</b>



**Farasan Islands Locator Map**







**Farasan Islands Bathymetry**

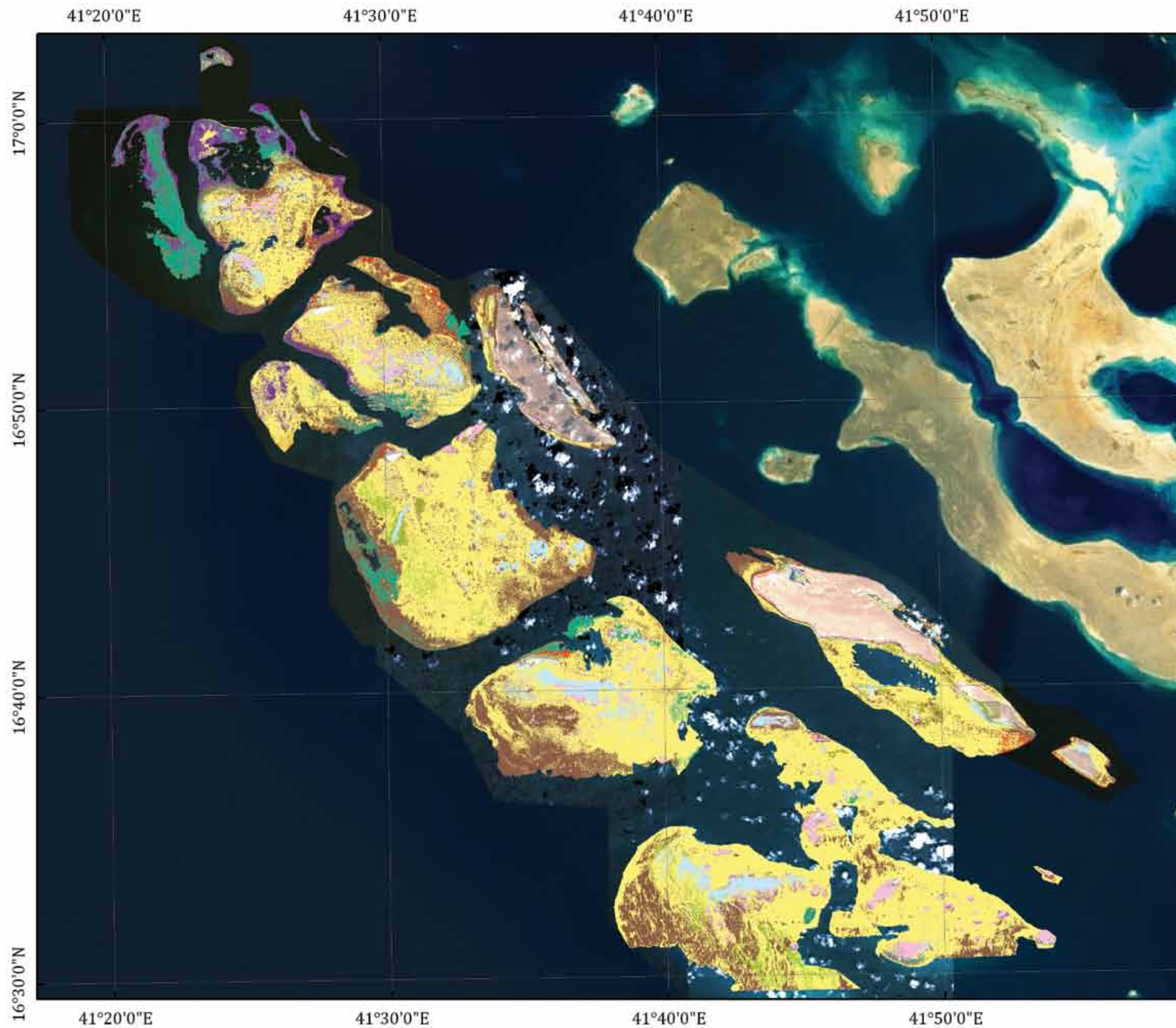
**Depth, meters**

0 - 0.9	12 - 12.9
1 - 1.9	13 - 13.9
2 - 2.9	14 - 14.9
3 - 3.9	15 - 15.9
4 - 4.9	16 - 16.9
5 - 5.9	17 - 17.9
6 - 6.9	18 - 18.9
7 - 7.9	19 - 19.9
8 - 8.9	20 - 20.9
9 - 9.9	Deep water
10 - 10.9	Clouds
11 - 11.9	



**1:260,000**





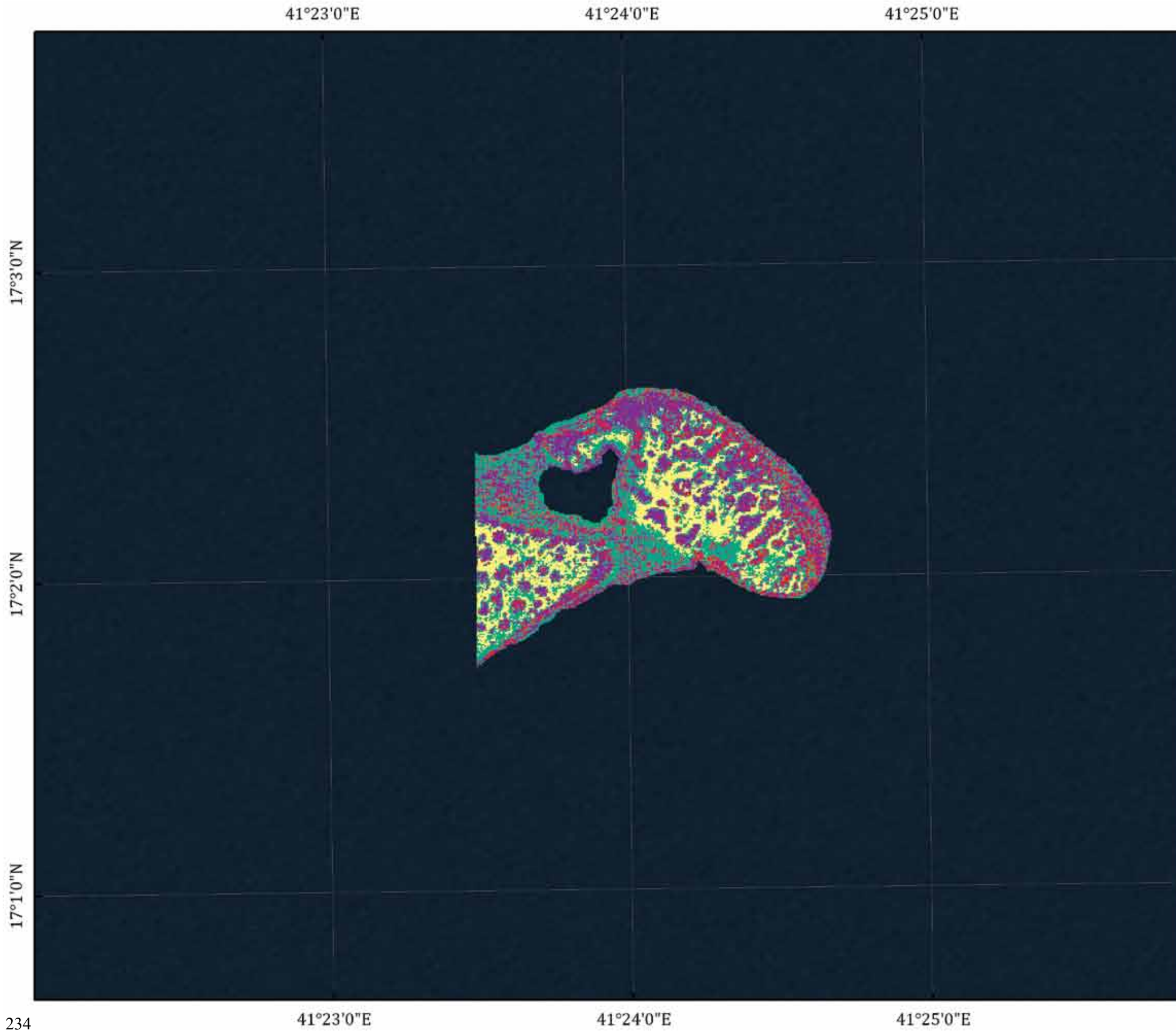
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1:260,000





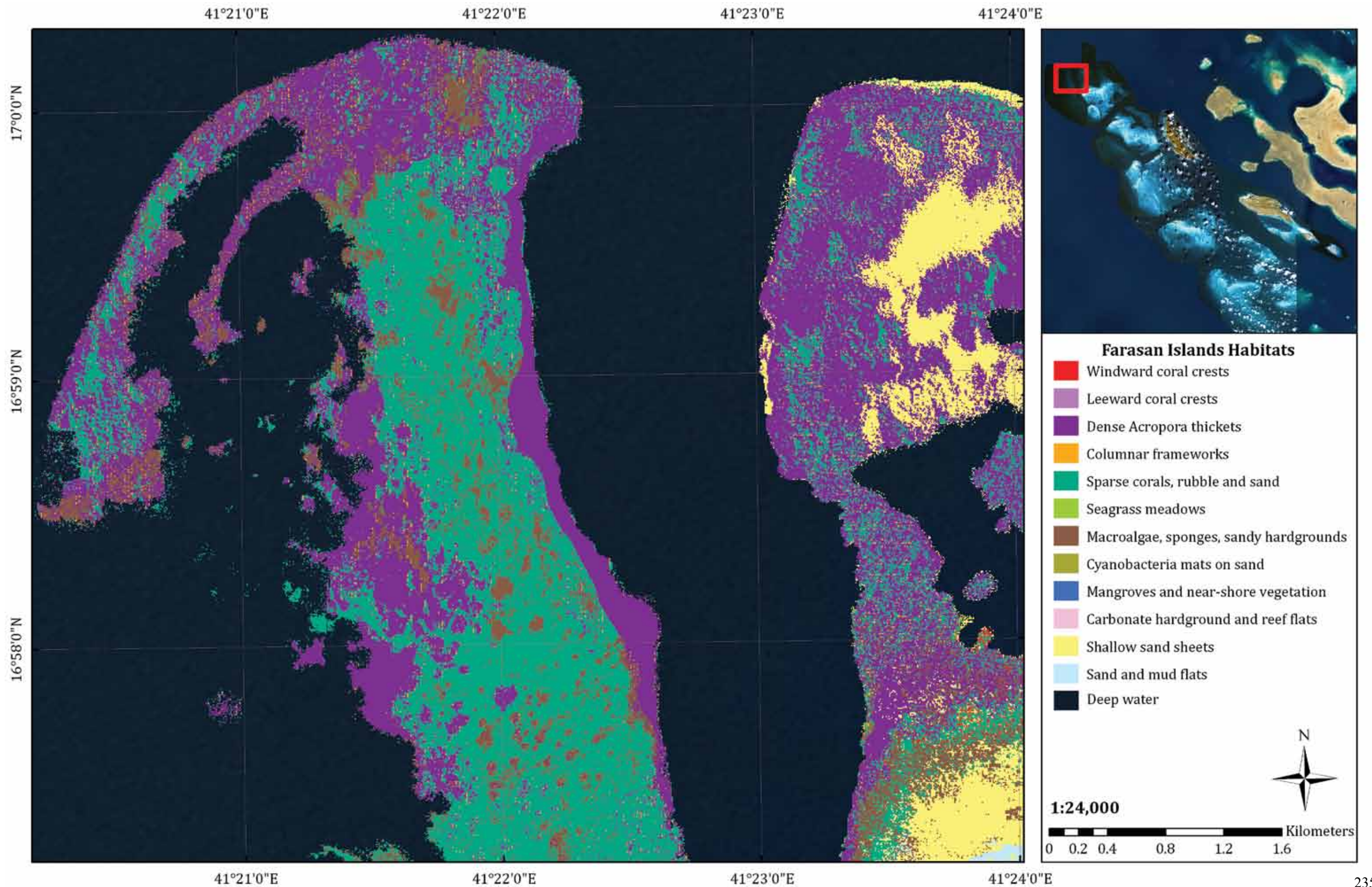
**Farasan Islands Habitats**

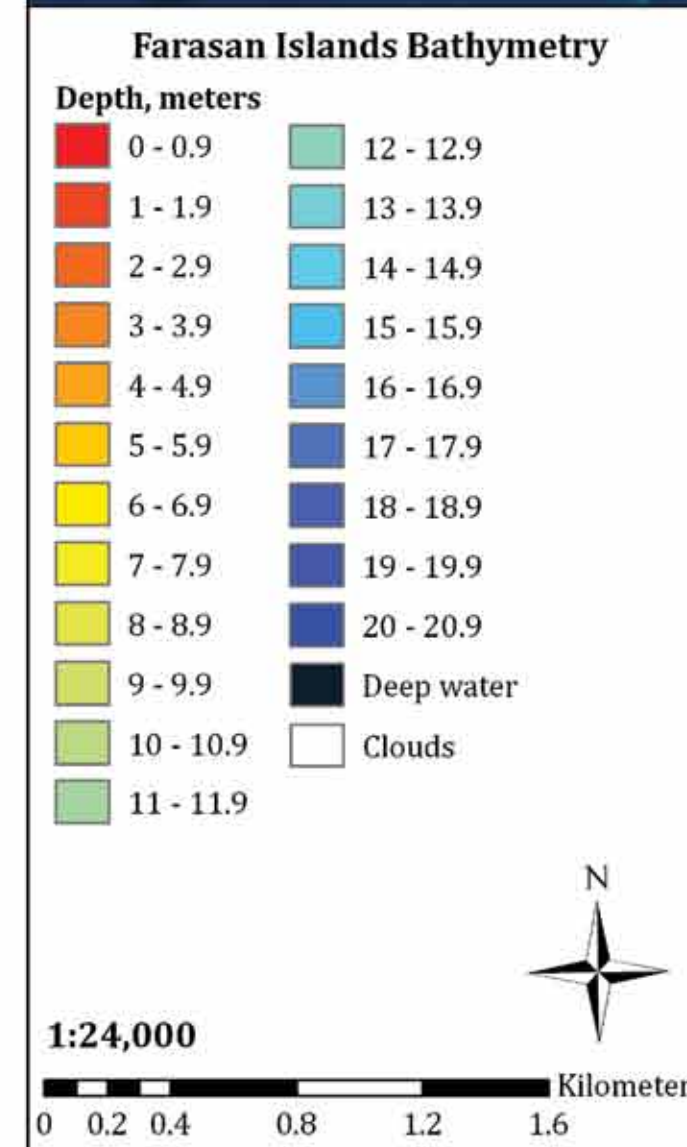
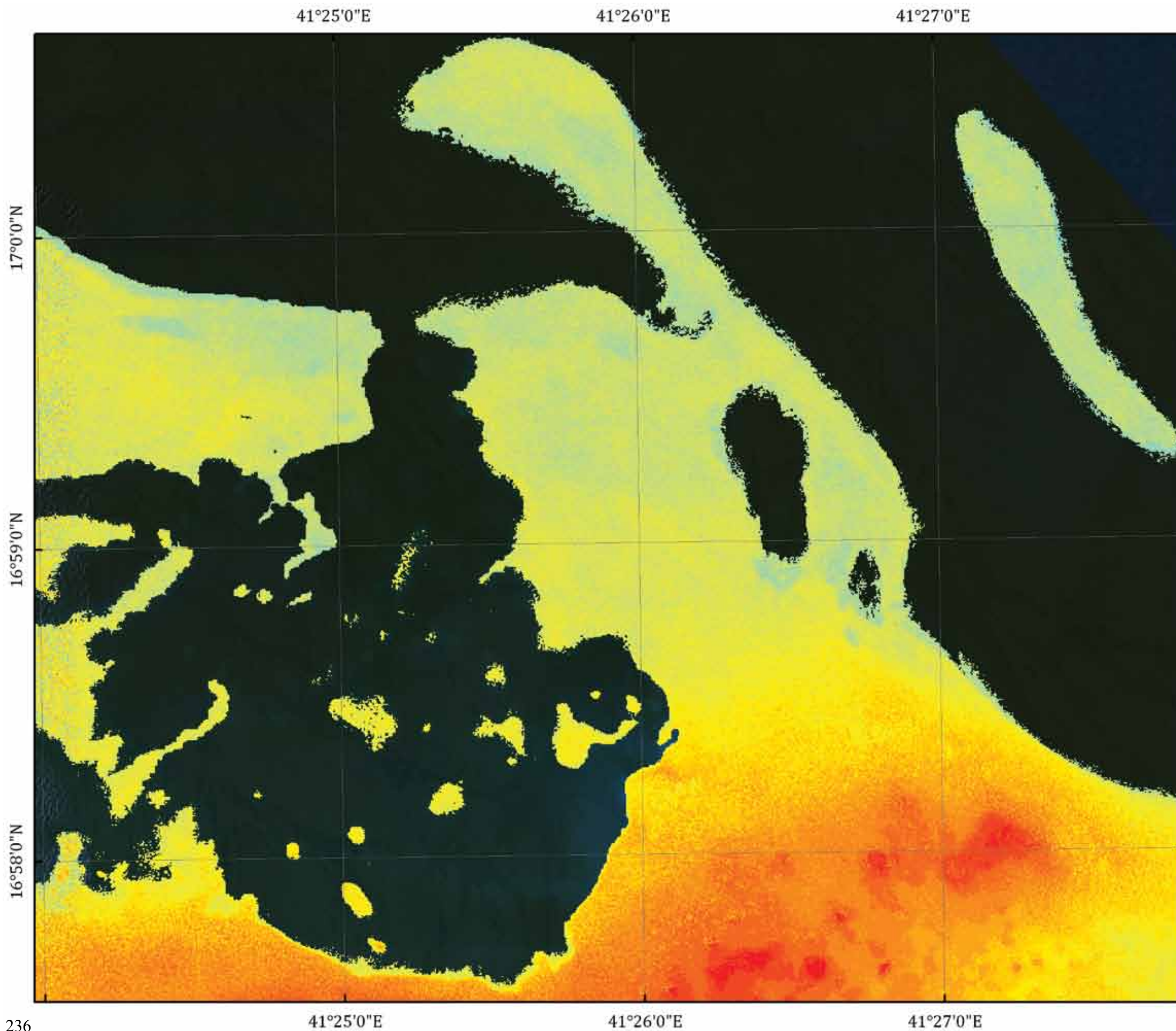
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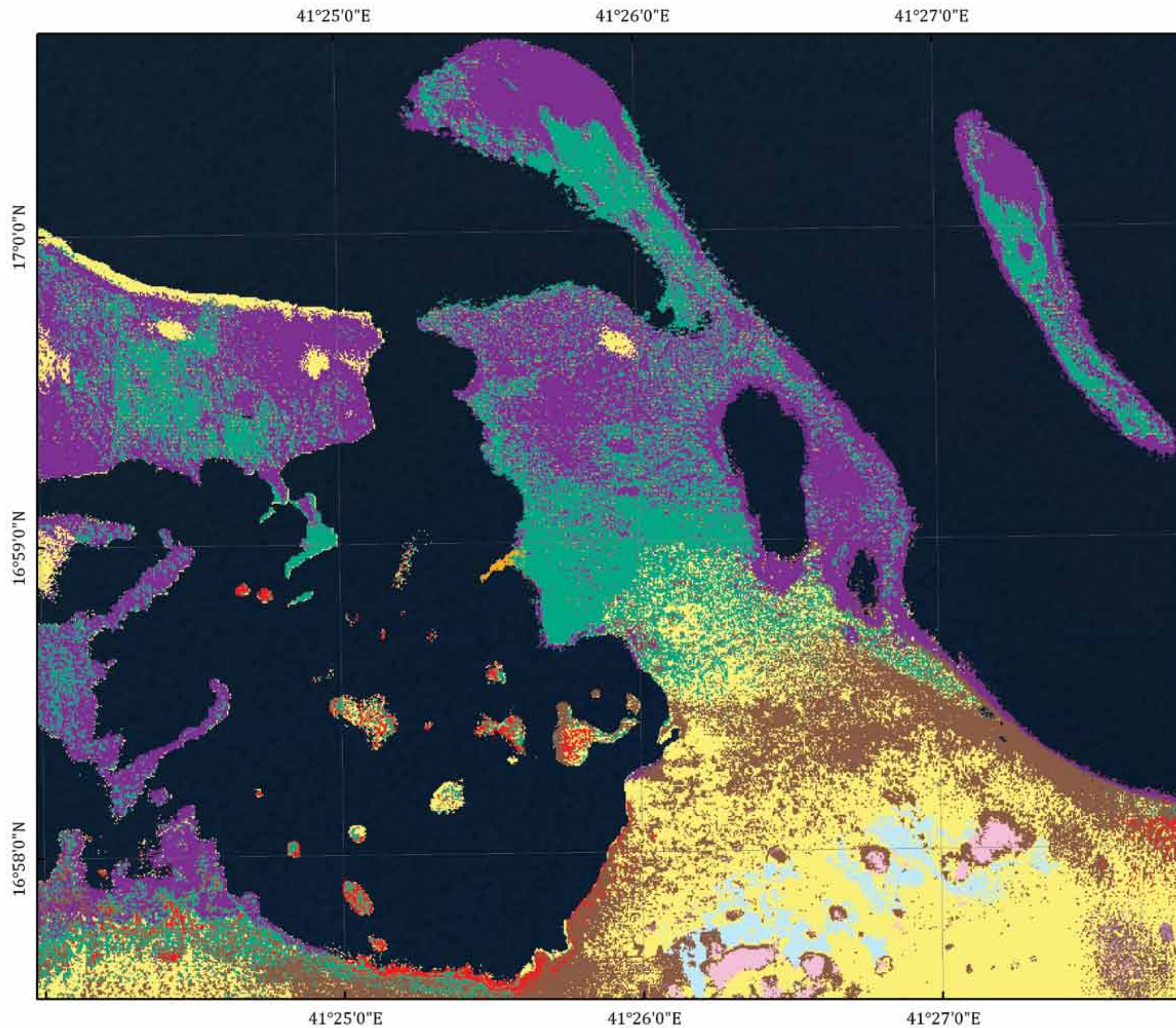
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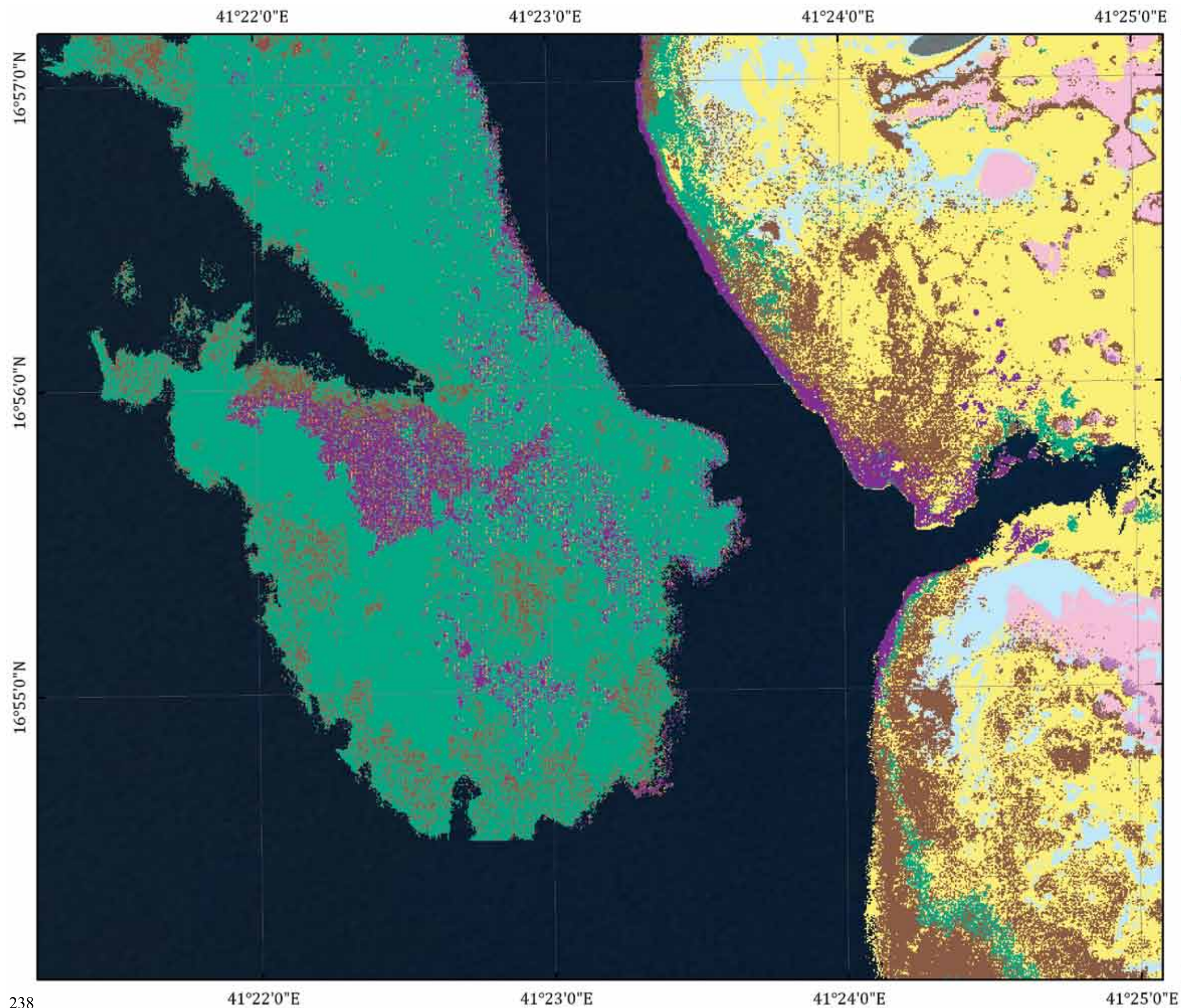
**1:24,000**

Kilometers









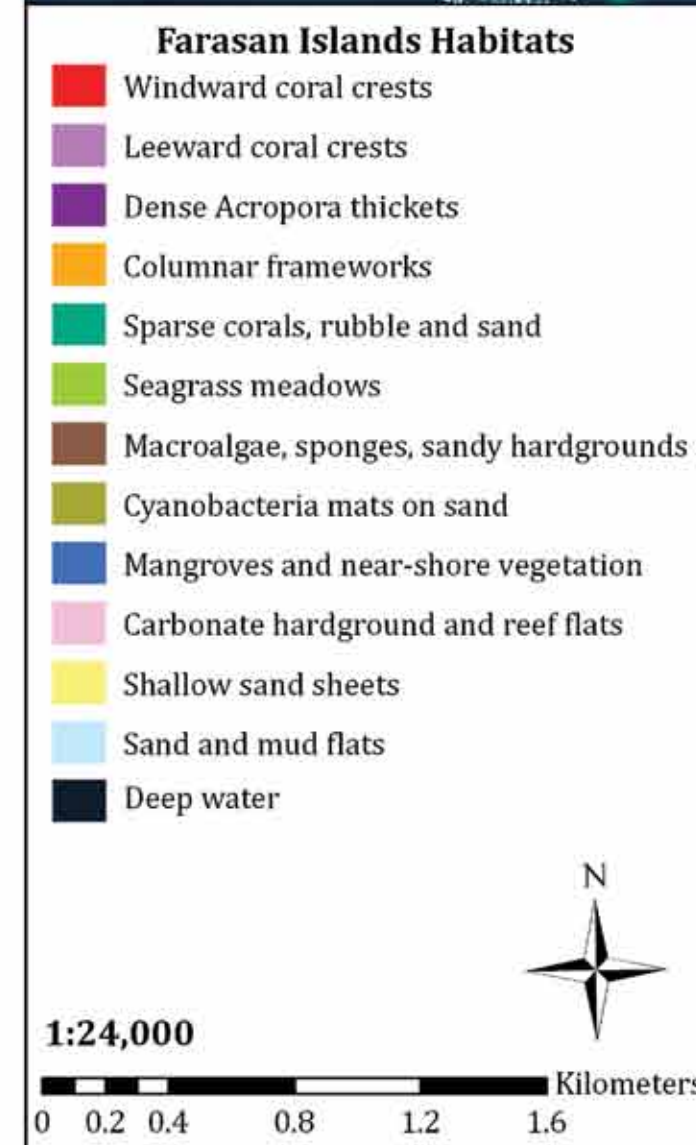
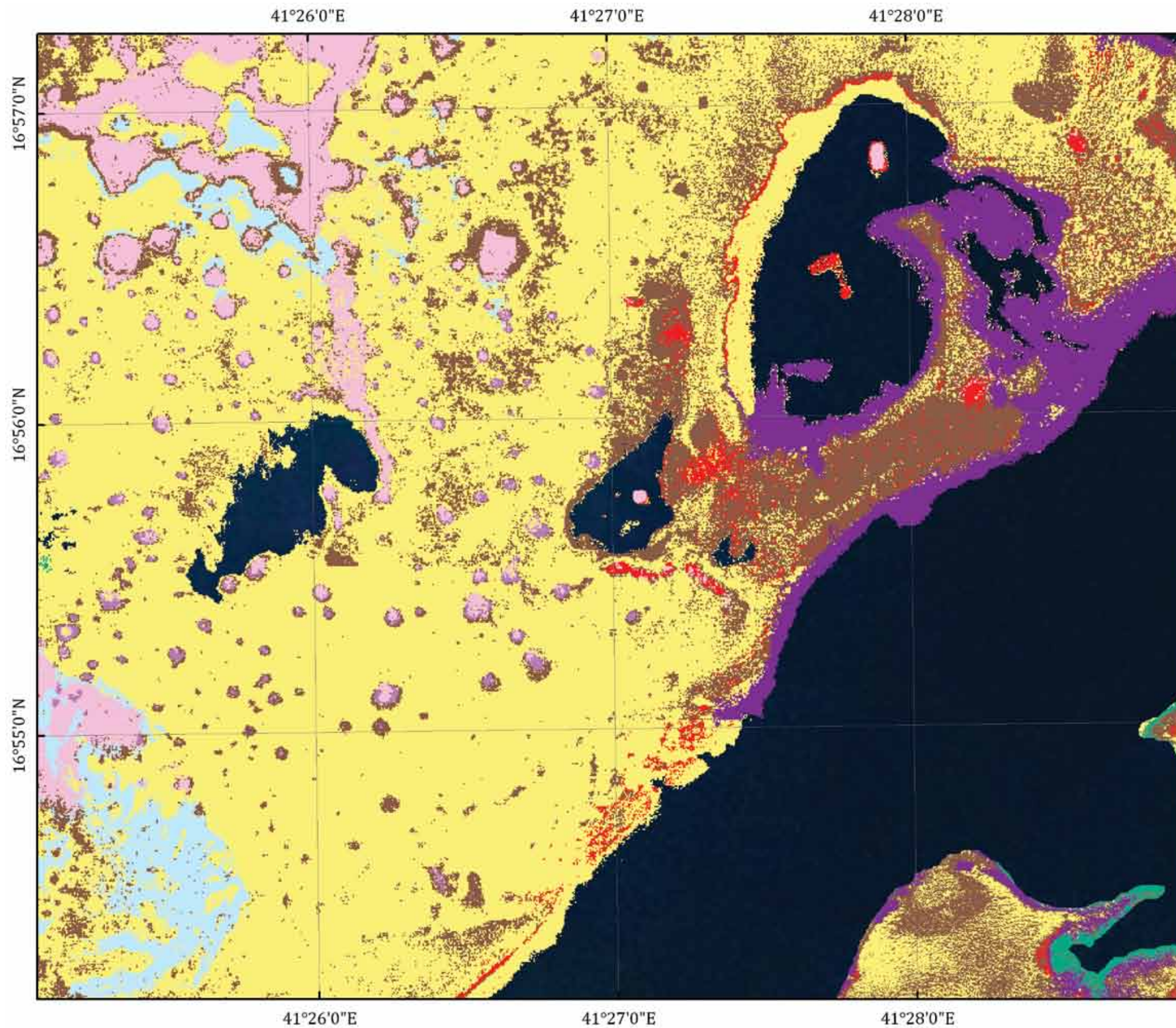
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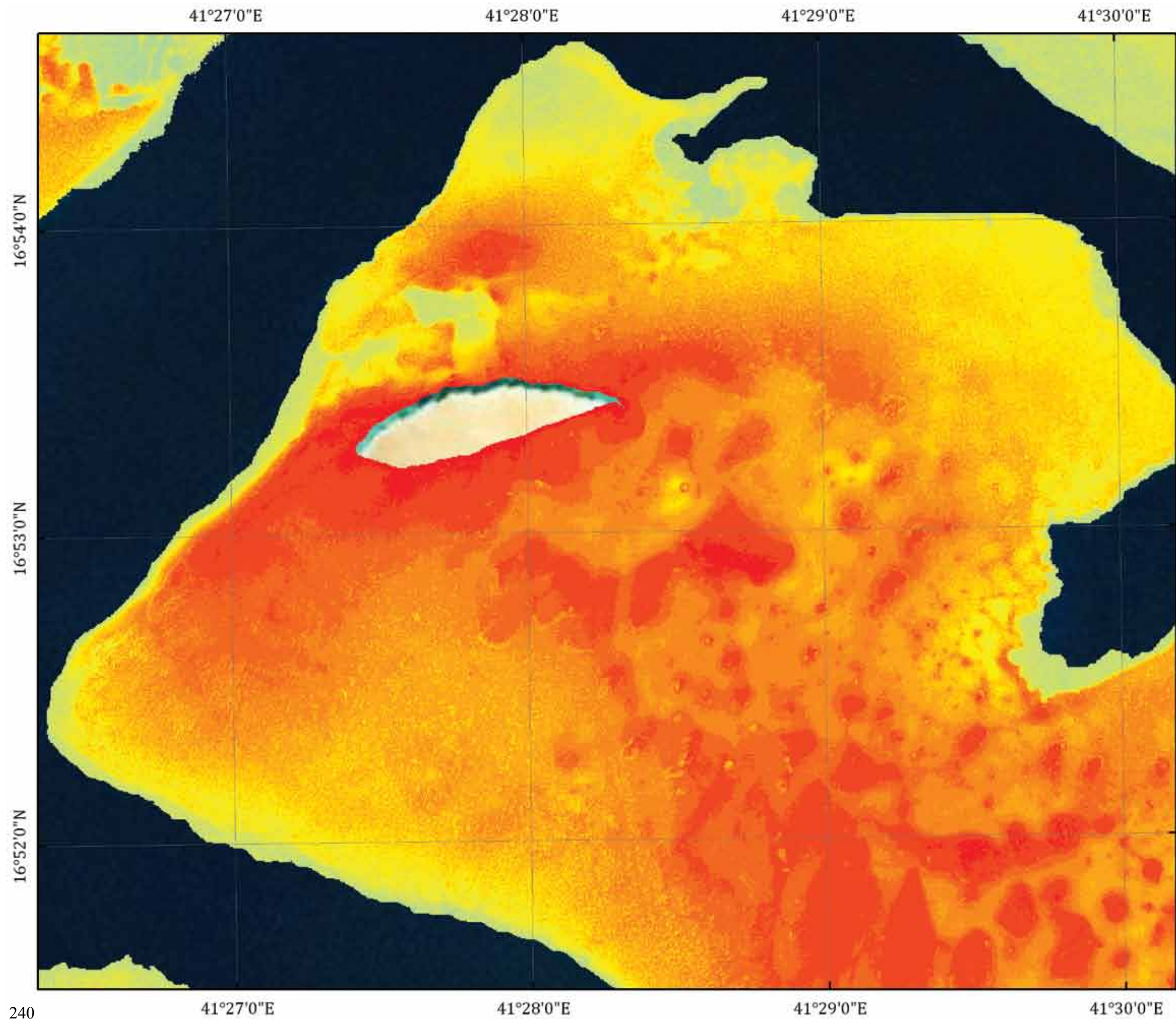


**1:24,000**









**Farasan Islands Bathymetry**

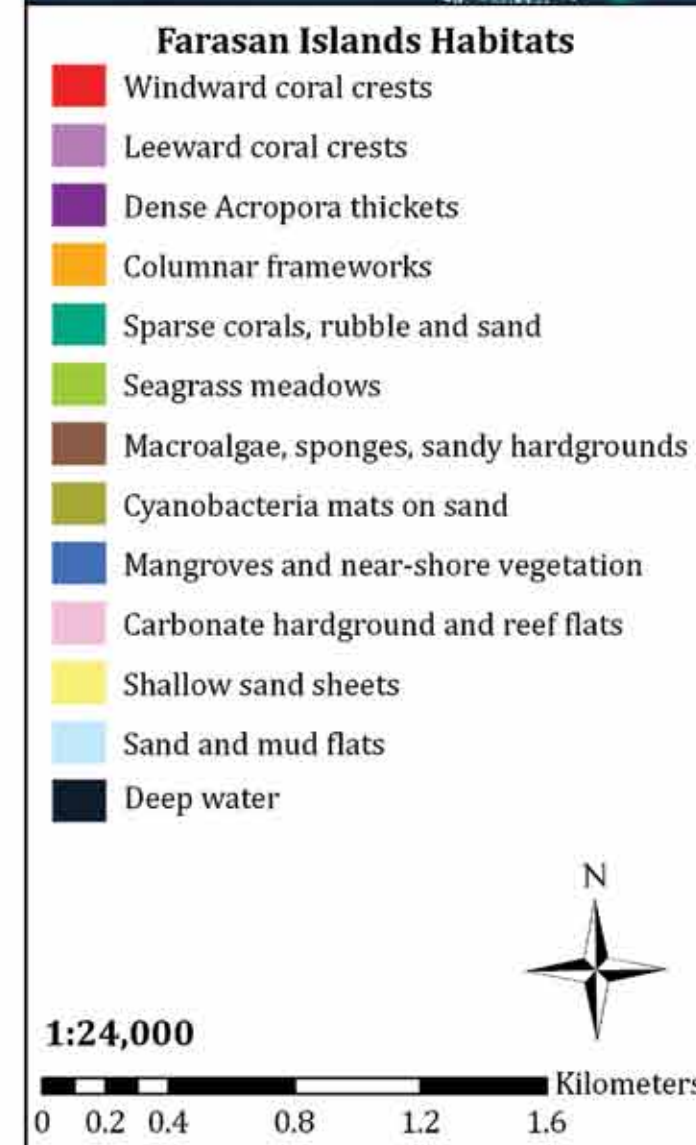
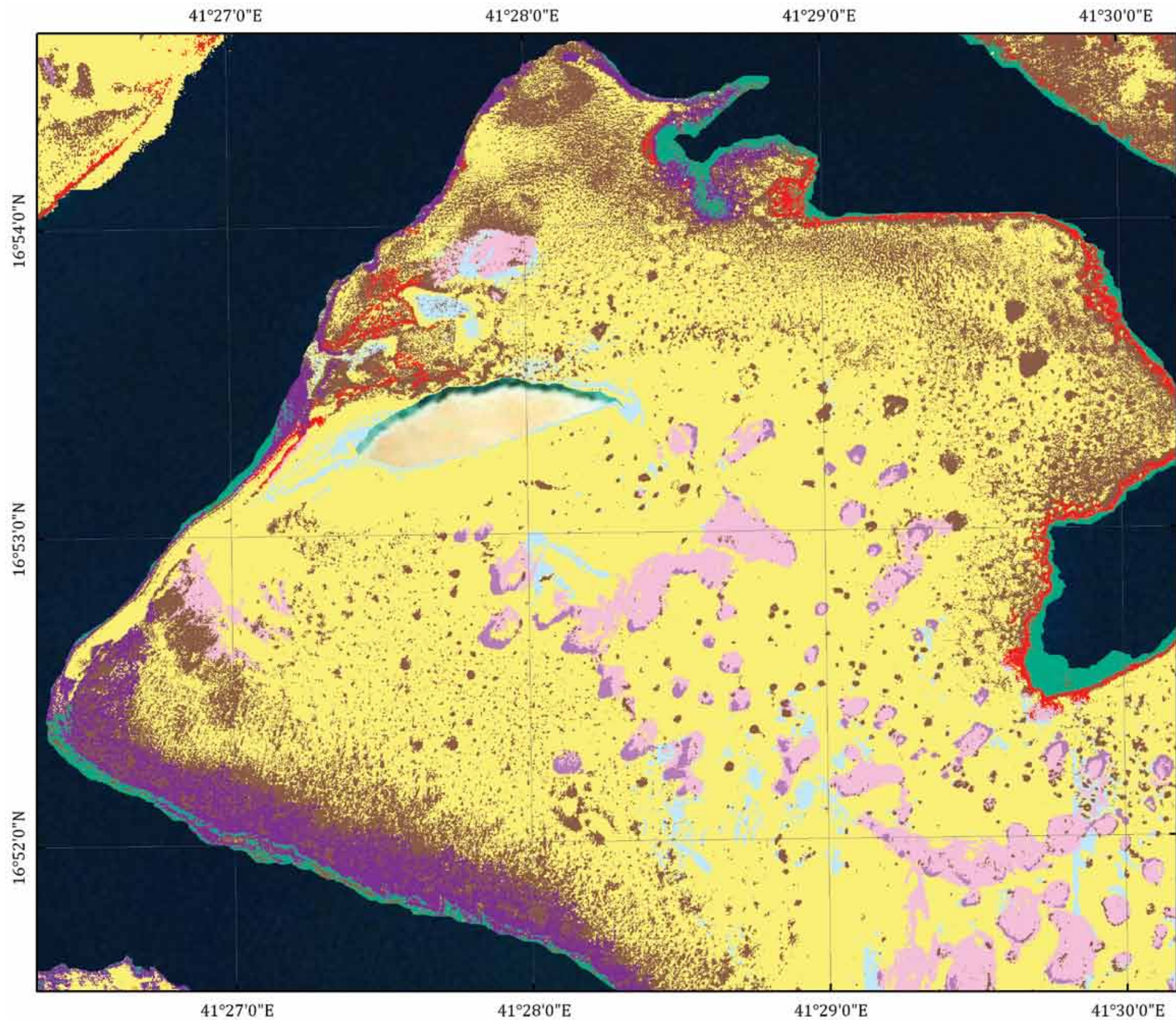
**Depth, meters**

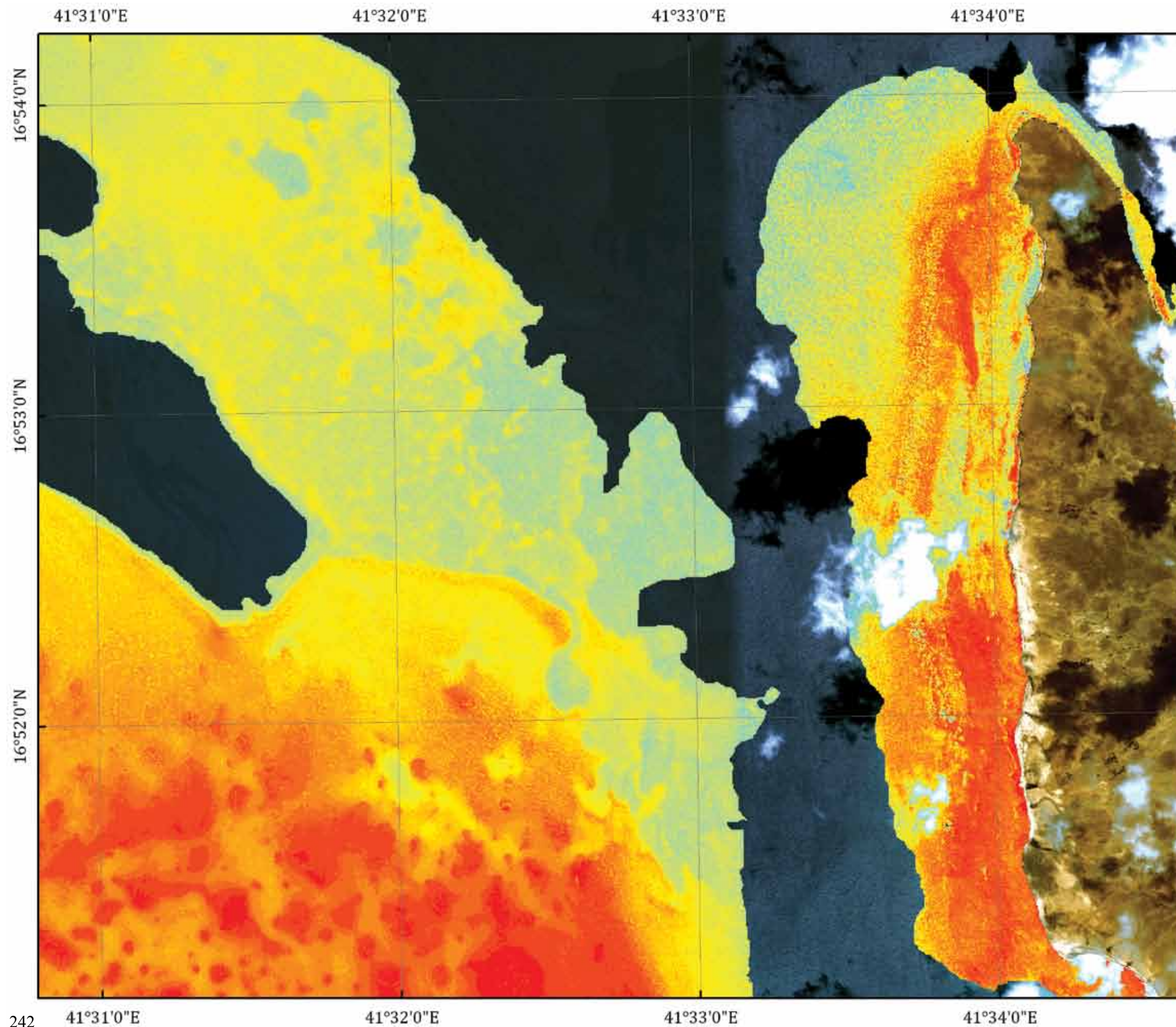
0 - 0.9	12 - 12.9
1 - 1.9	13 - 13.9
2 - 2.9	14 - 14.9
3 - 3.9	15 - 15.9
4 - 4.9	16 - 16.9
5 - 5.9	17 - 17.9
6 - 6.9	18 - 18.9
7 - 7.9	19 - 19.9
8 - 8.9	20 - 20.9
9 - 9.9	Deep water
10 - 10.9	Clouds
11 - 11.9	



**1:24,000**







**Farasan Islands Bathymetry**

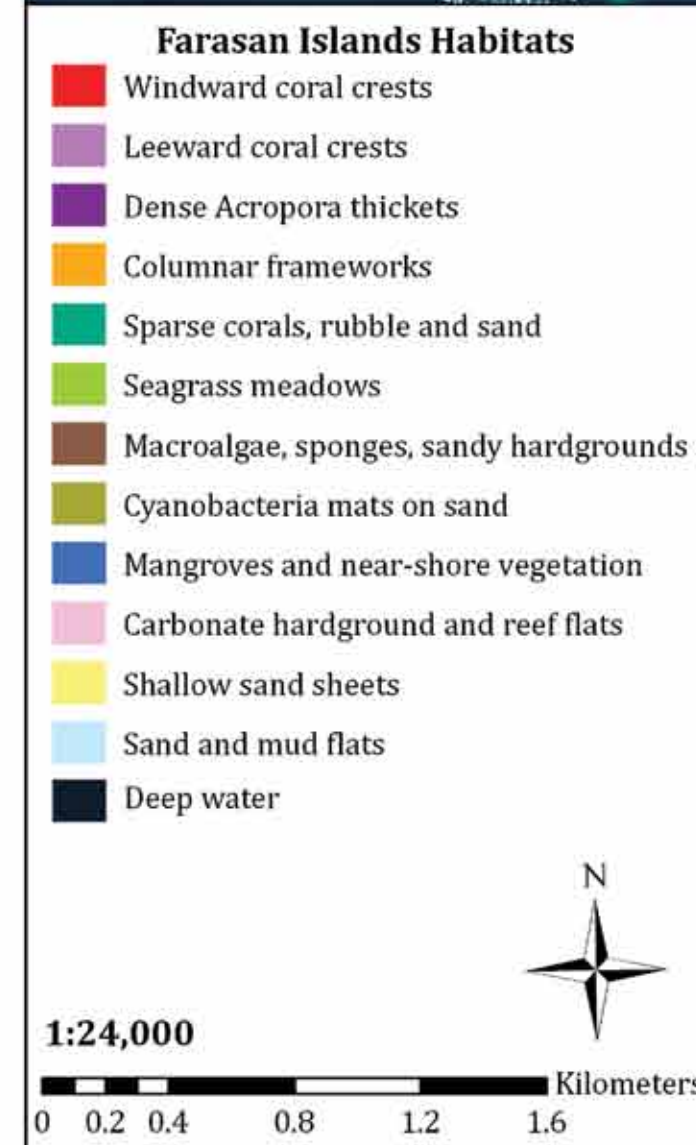
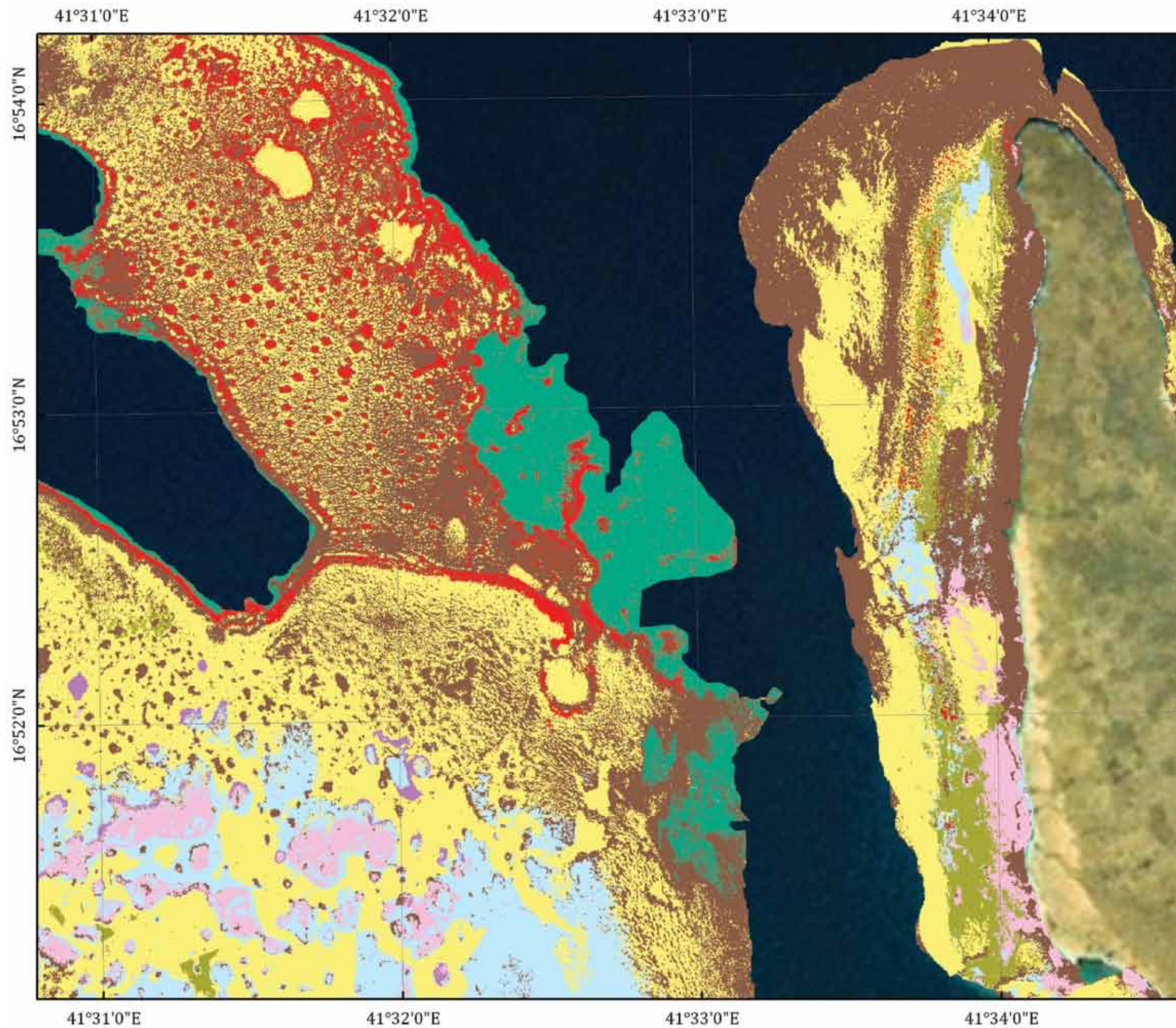
**Depth, meters**

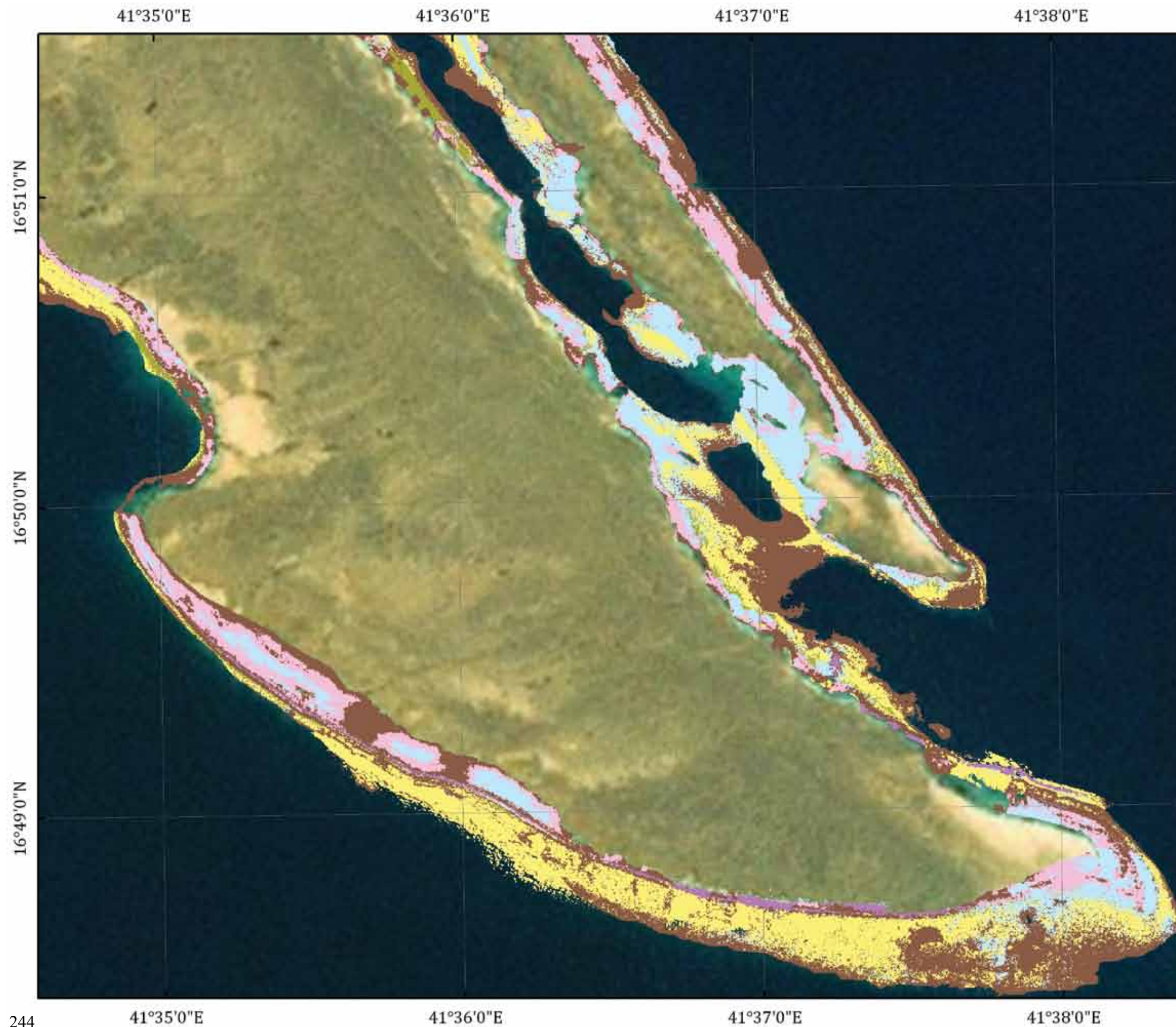
0 - 0.9	12 - 12.9
1 - 1.9	13 - 13.9
2 - 2.9	14 - 14.9
3 - 3.9	15 - 15.9
4 - 4.9	16 - 16.9
5 - 5.9	17 - 17.9
6 - 6.9	18 - 18.9
7 - 7.9	19 - 19.9
8 - 8.9	20 - 20.9
9 - 9.9	Deep water
10 - 10.9	Clouds
11 - 11.9	



**1:24,000**

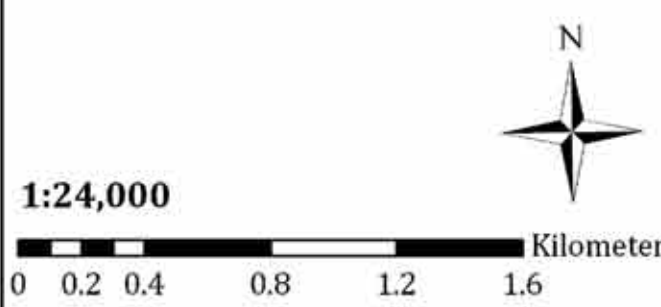


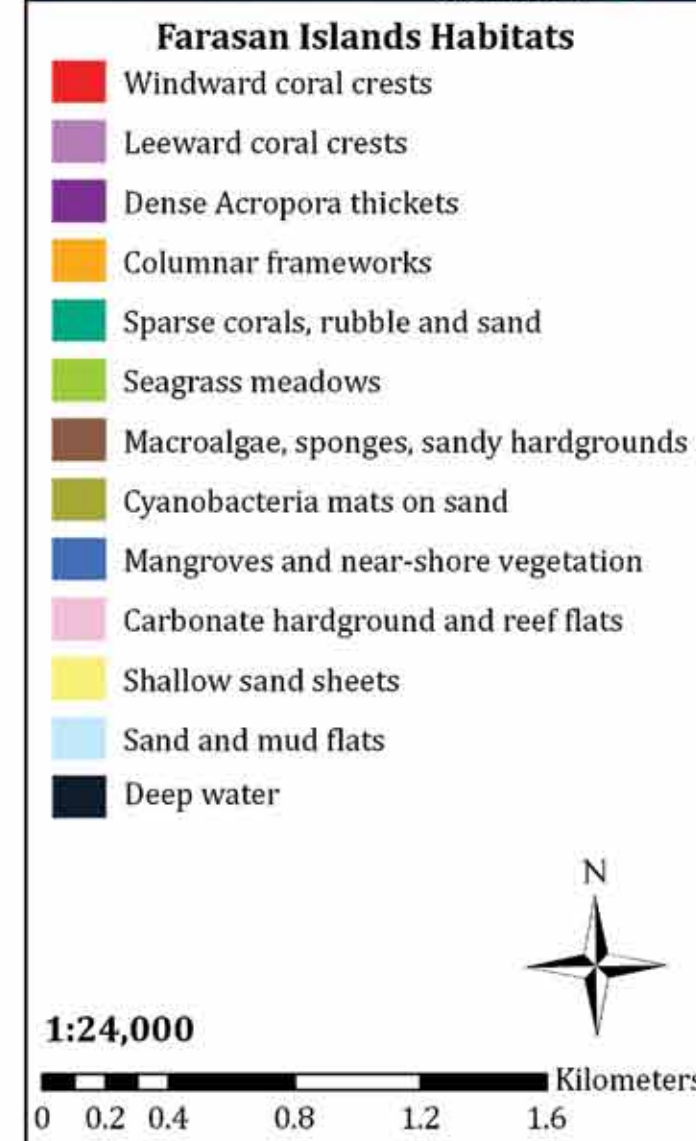
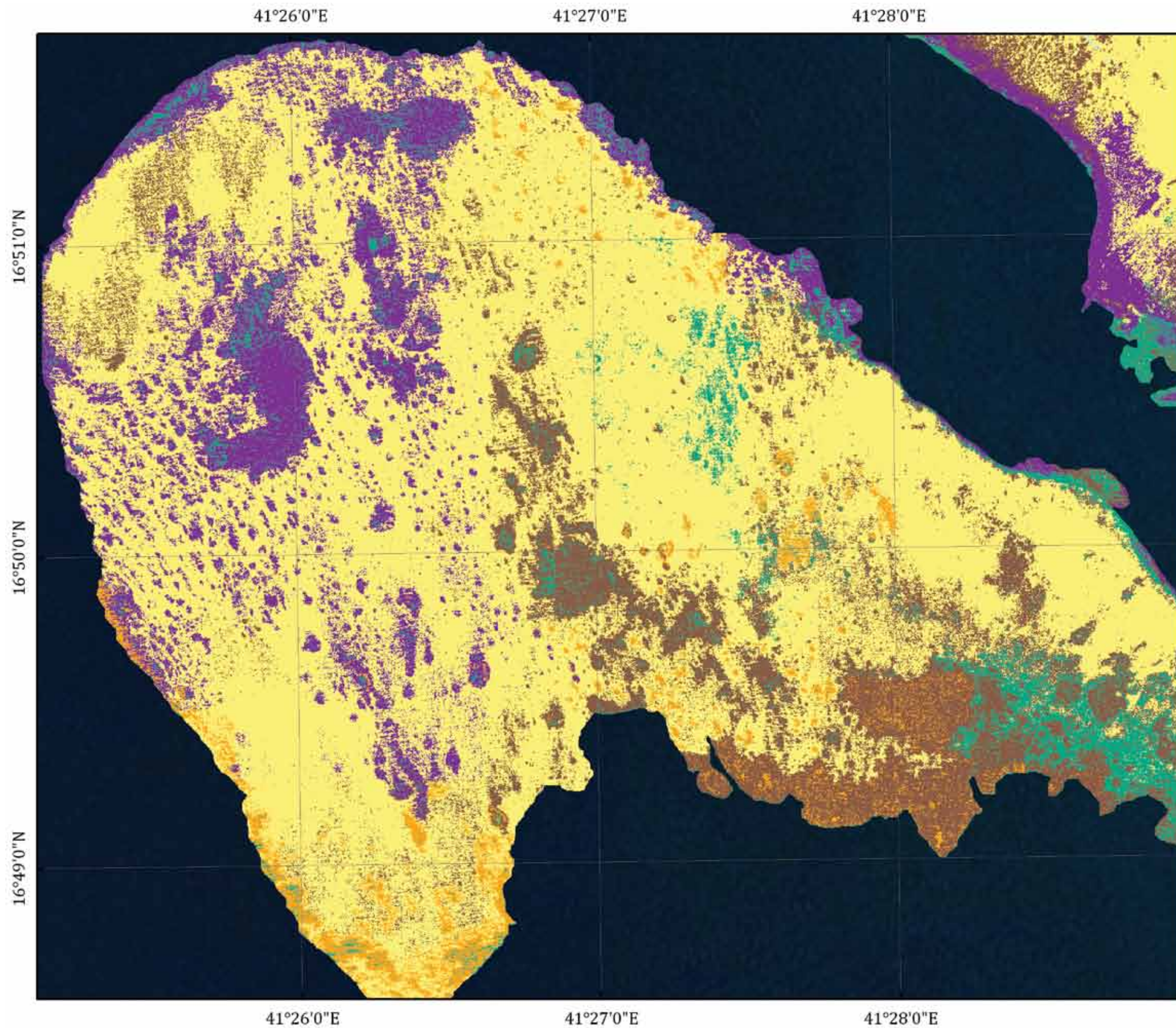


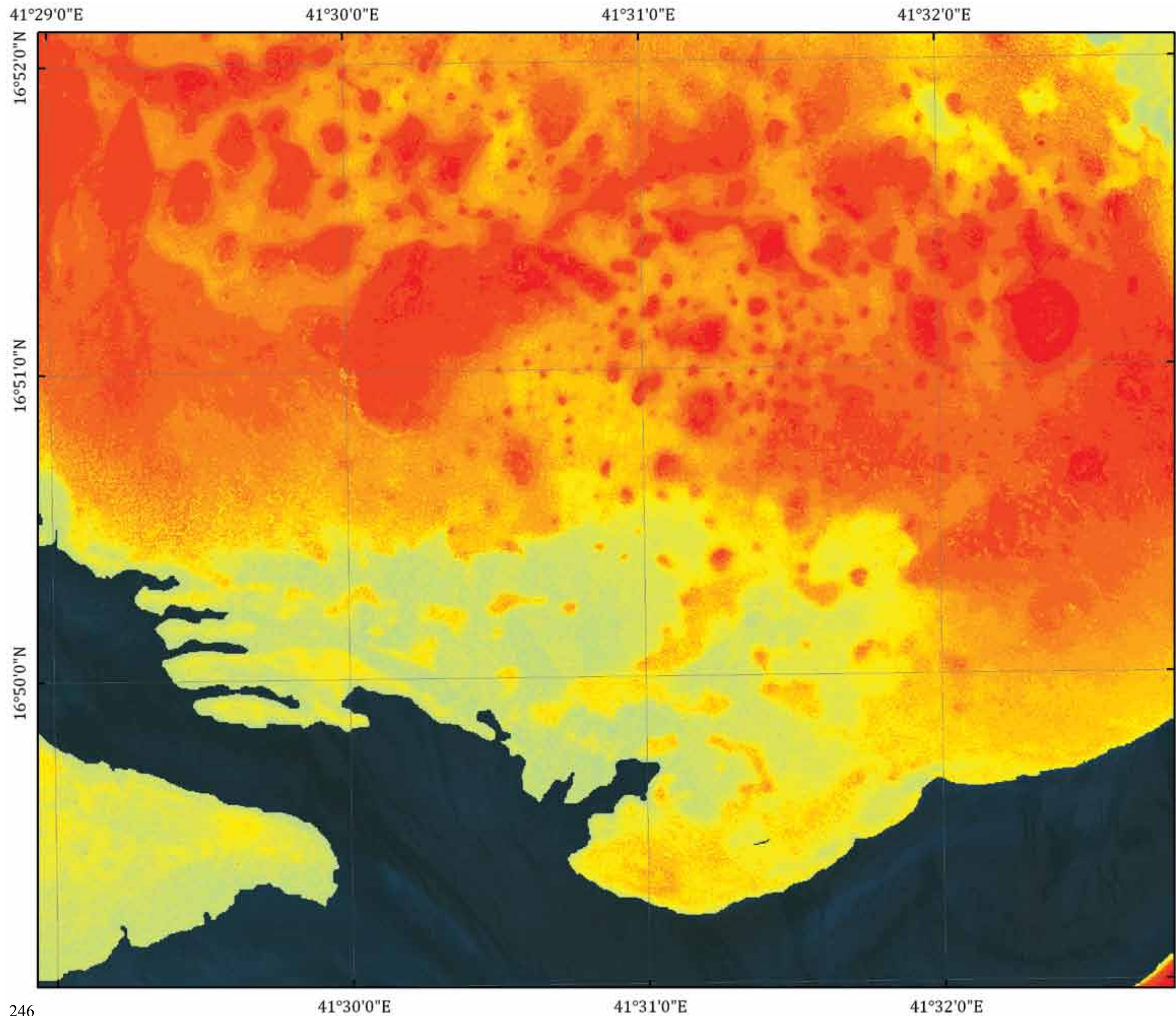


**Farasan Islands Habitats**

- Windward coral crests
- Leeward coral crests
- Dense Acropora thickets
- Columnar frameworks
- Sparse corals, rubble and sand
- Seagrass meadows
- Macroalgae, sponges, sandy hardgrounds
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- Mangroves and near-shore vegetation
- Carbonate hardground and reef flats
- Shallow sand sheets
- Sand and mud flats
- Deep water



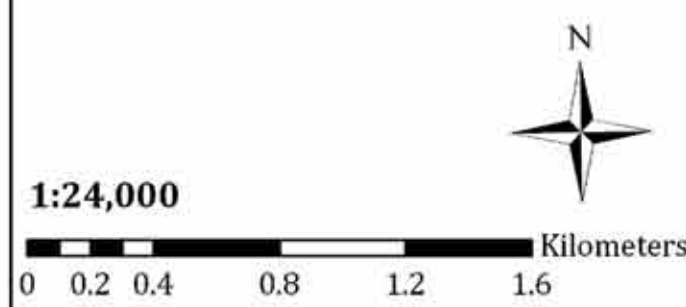




**Farasan Islands Bathymetry**

**Depth, meters**

0 - 0.9	12 - 12.9
1 - 1.9	13 - 13.9
2 - 2.9	14 - 14.9
3 - 3.9	15 - 15.9
4 - 4.9	16 - 16.9
5 - 5.9	17 - 17.9
6 - 6.9	18 - 18.9
7 - 7.9	19 - 19.9
8 - 8.9	20 - 20.9
9 - 9.9	Deep water
10 - 10.9	Clouds
11 - 11.9	



41°29'0"E

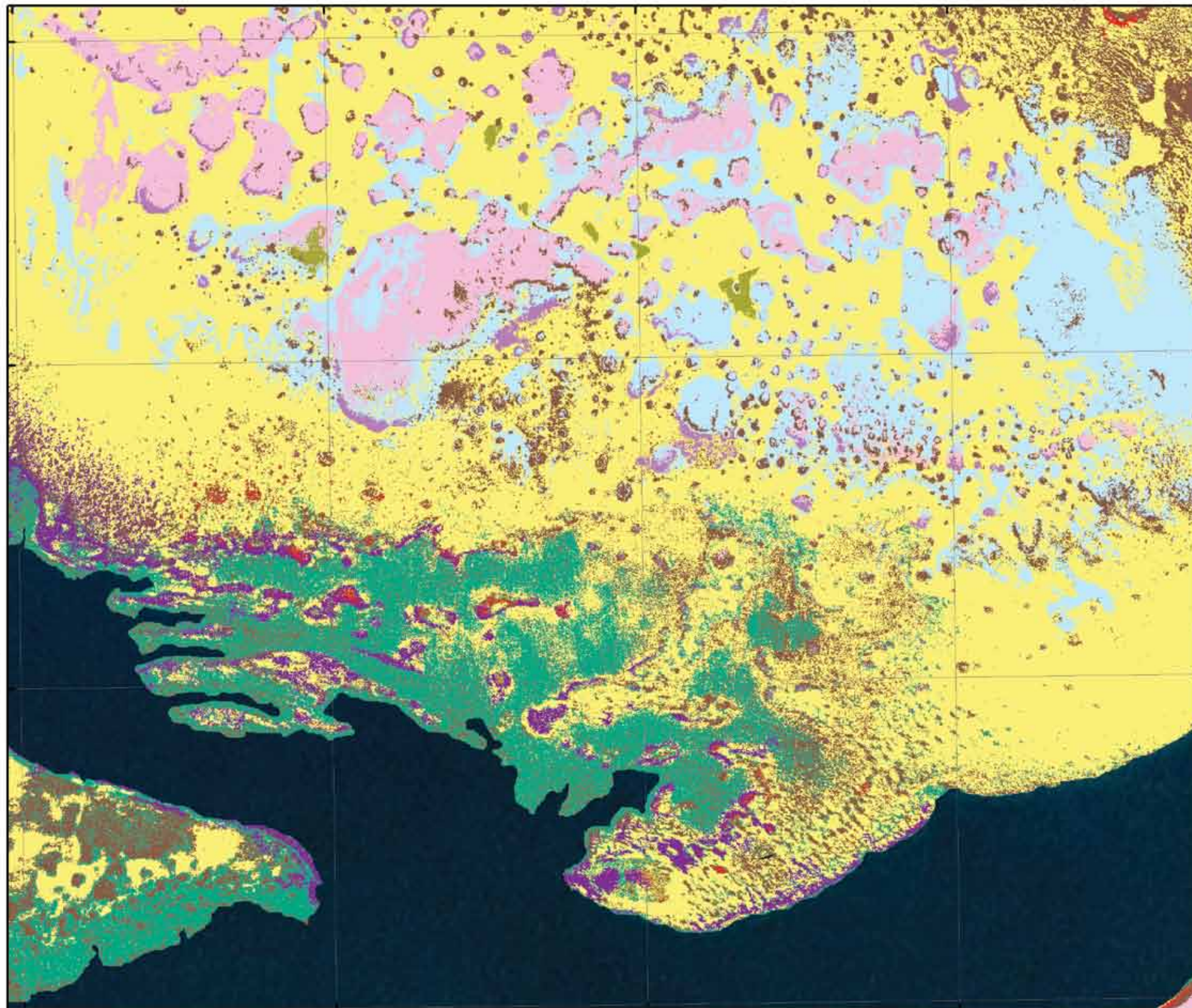
41°30'0"E

41°31'0"E

41°32'0"E

16°51'0"N

16°50'0"N



41°30'0"E

41°31'0"E

41°32'0"E

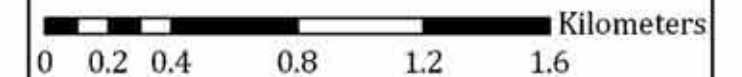


### Farasan Islands Habitats

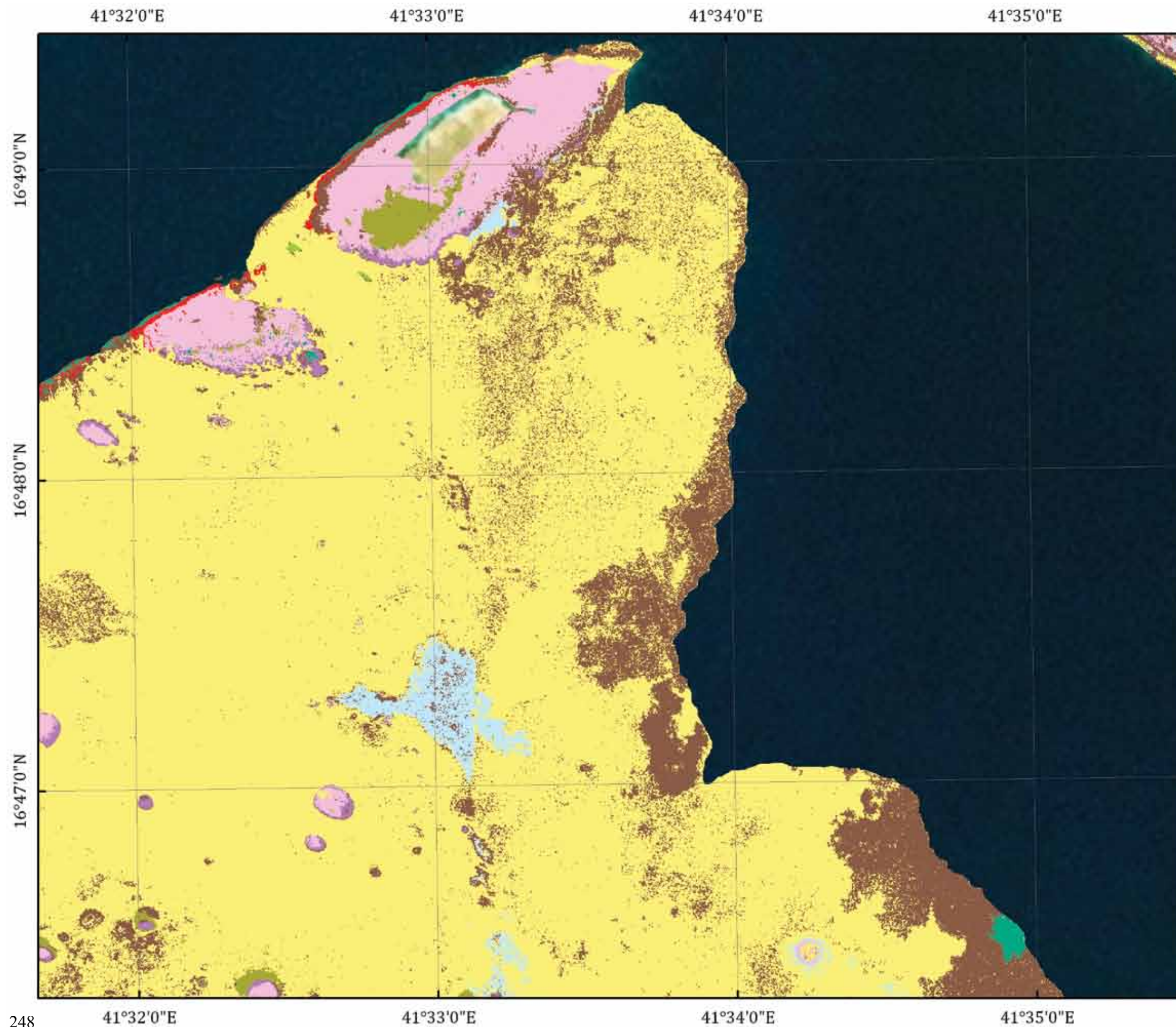
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- Sand and mud flats
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1:24,000







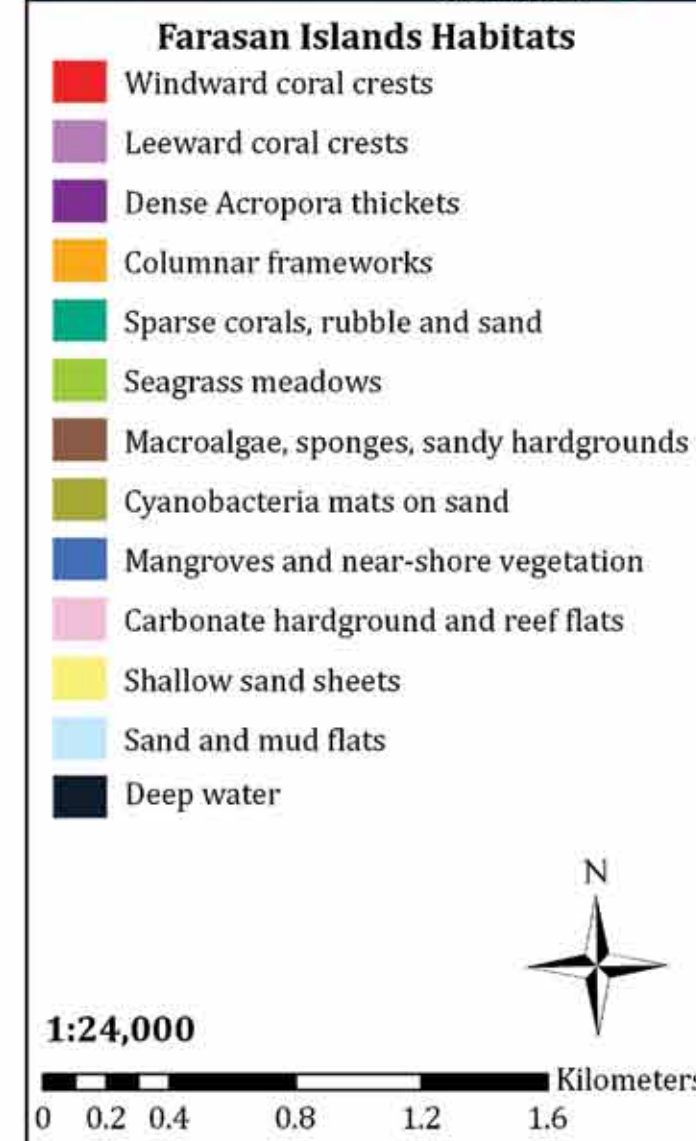
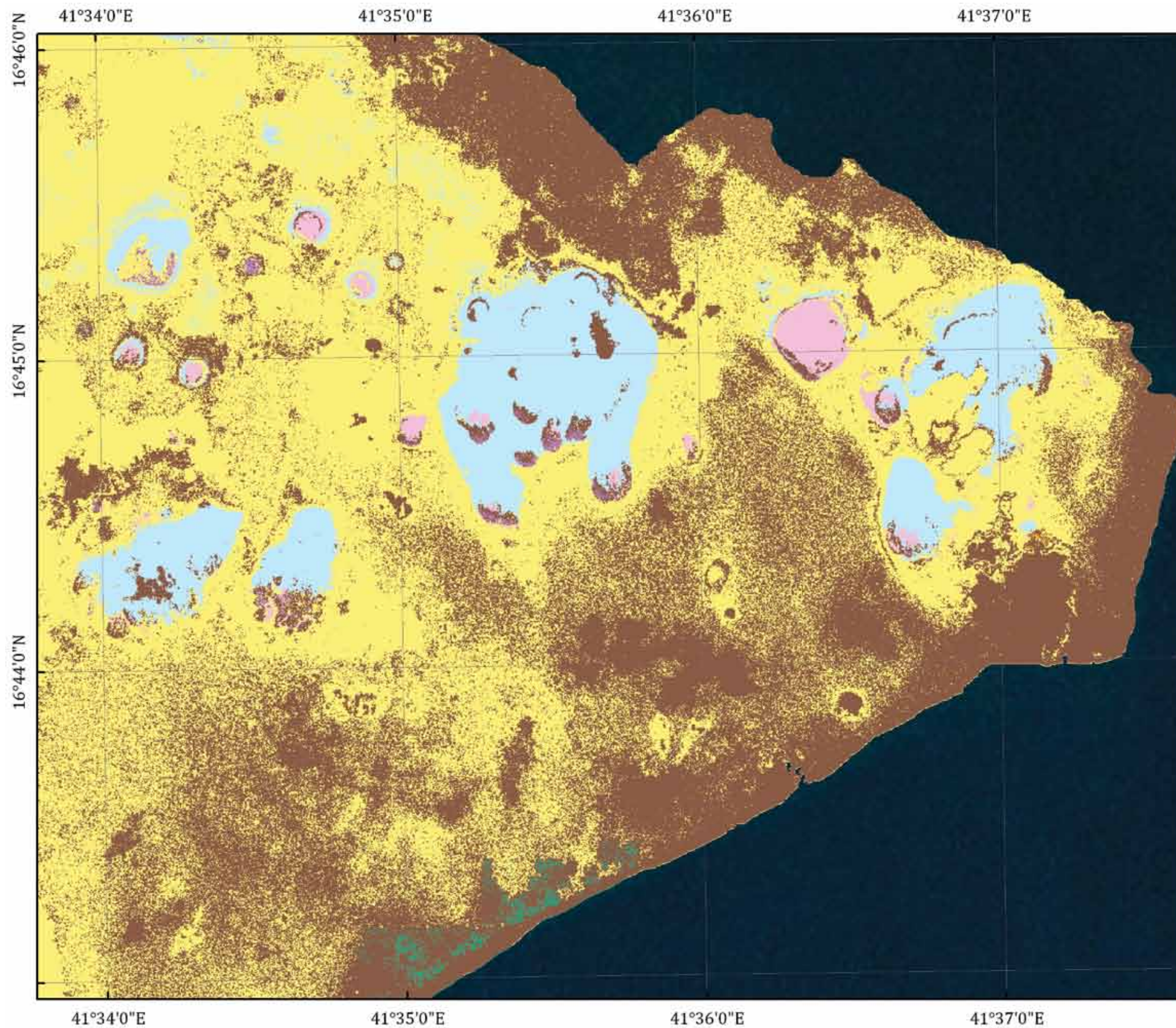
**Farasan Islands Habitats**

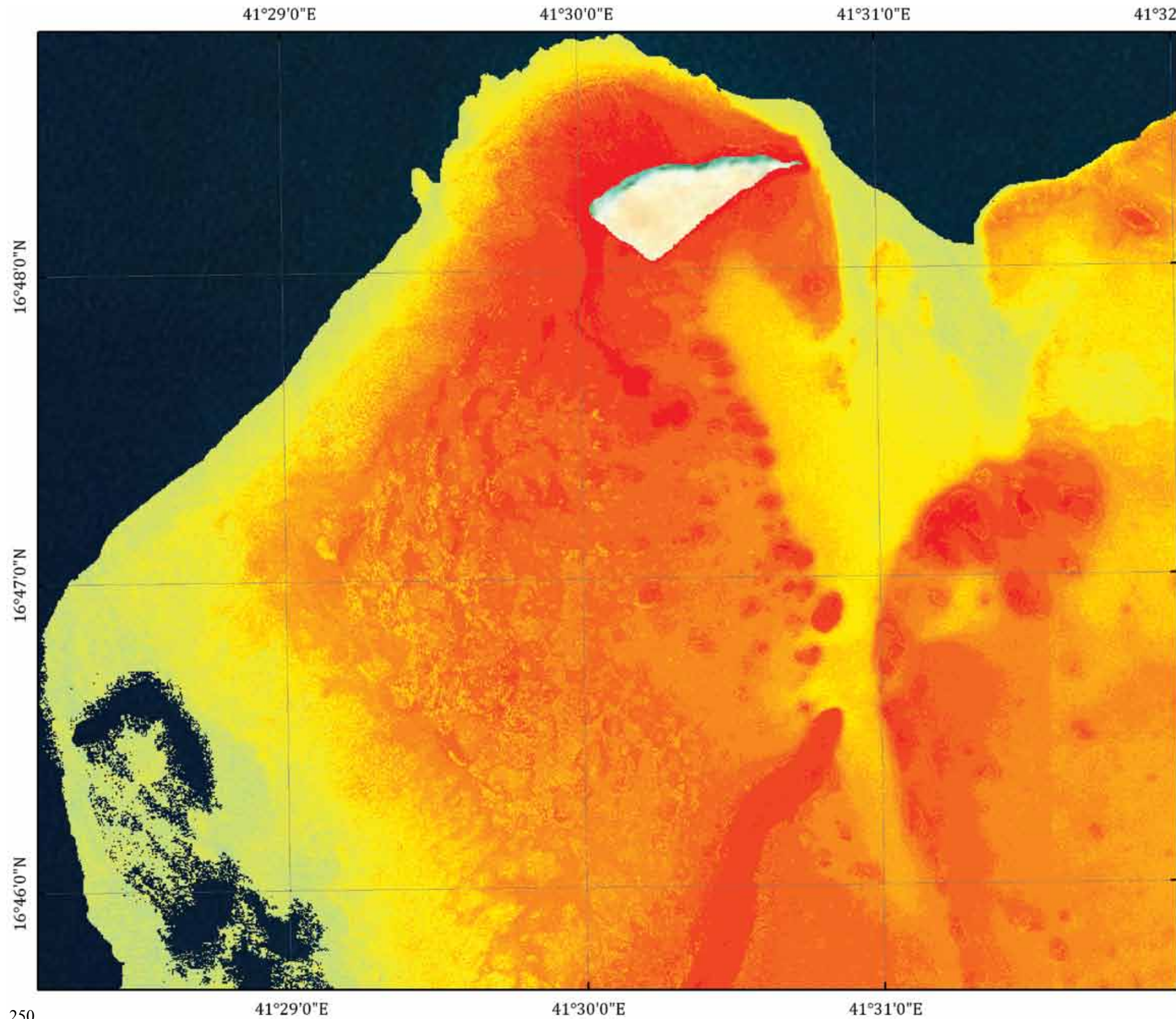
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**1:24,000**





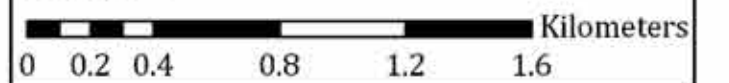


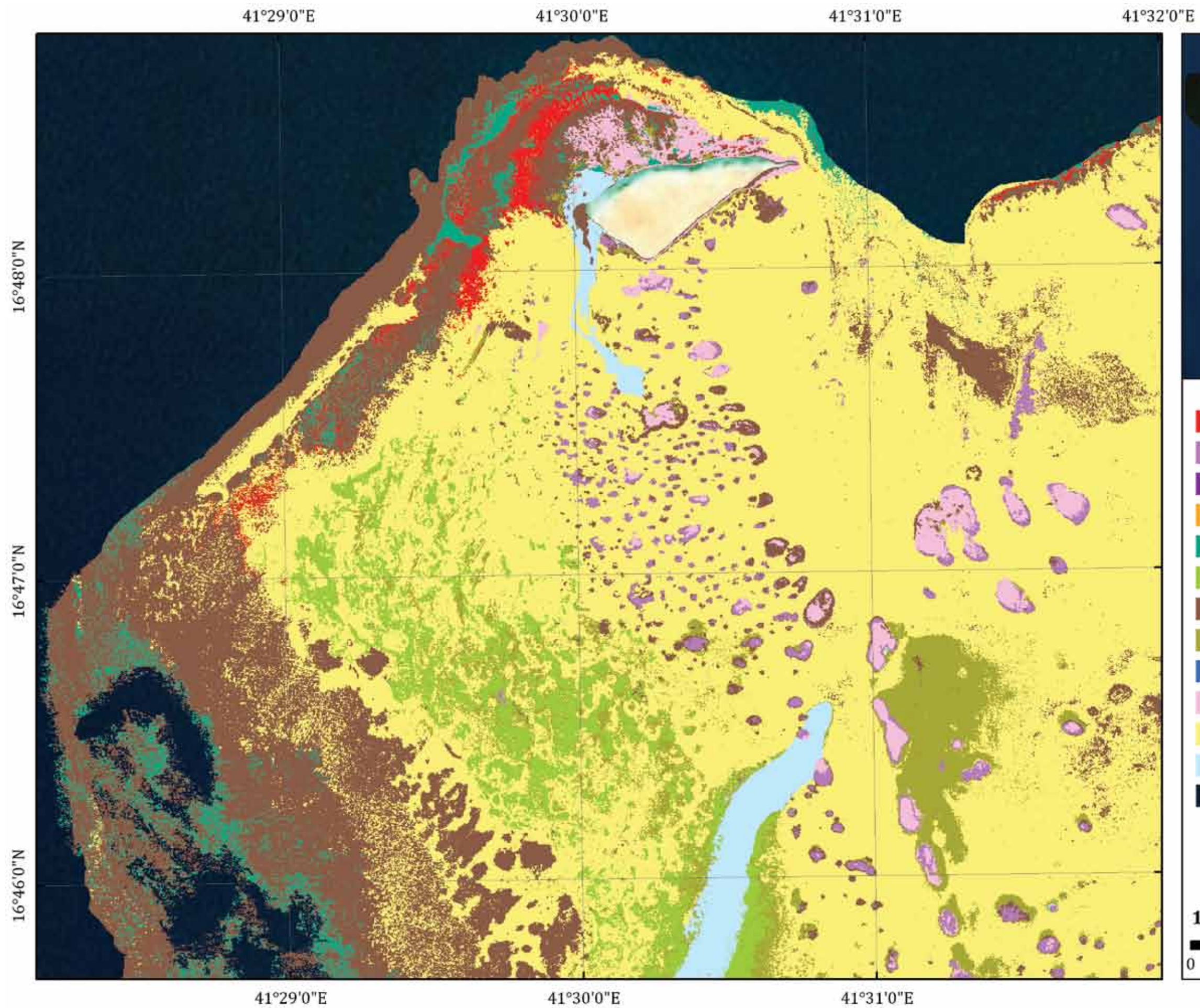
**Farasan Islands Bathymetry**

Depth, meters

0 - 0.9	12 - 12.9
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10 - 10.9	Clouds
11 - 11.9	


1:24,000






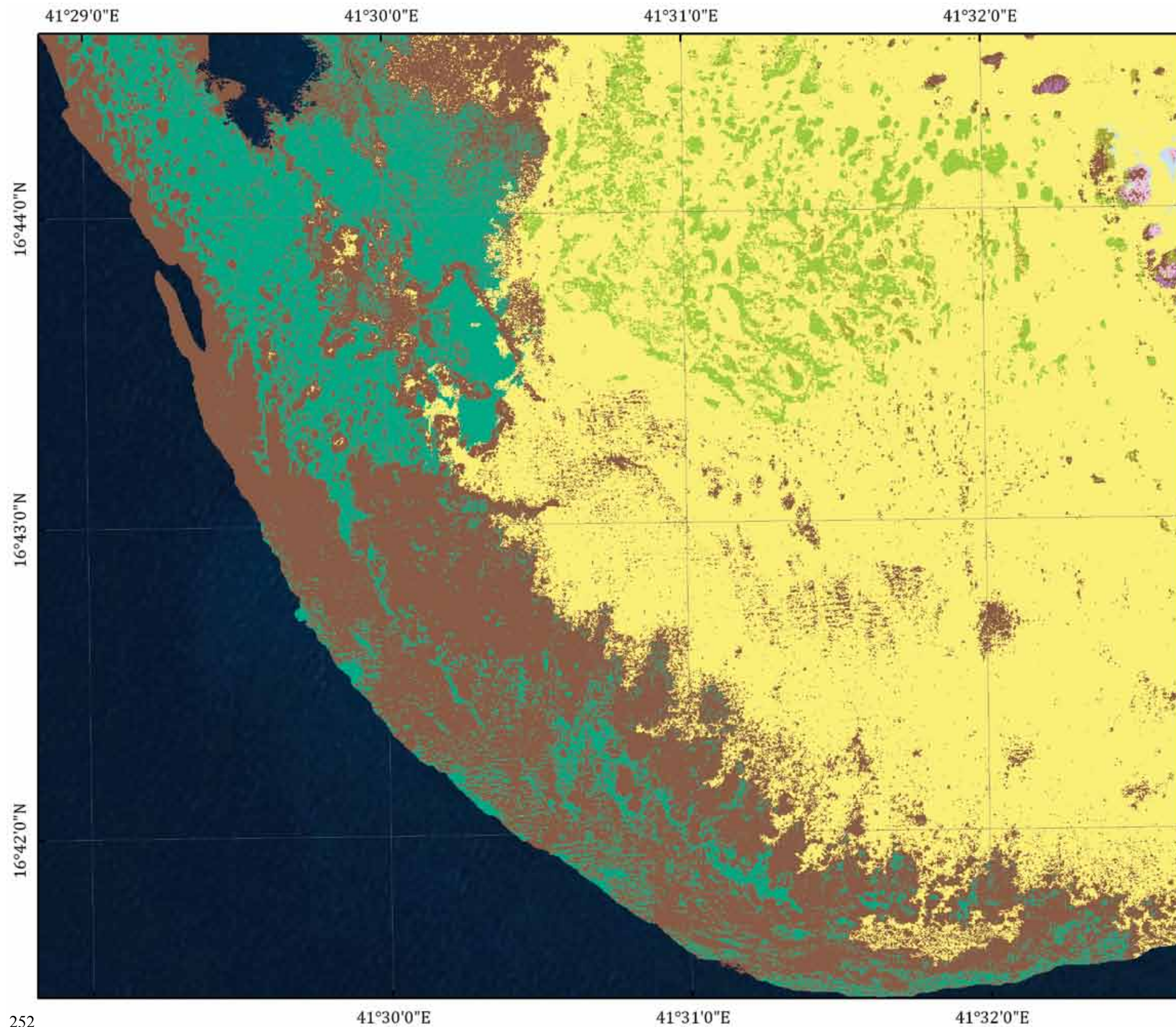
**Farasan Islands Habitats**

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- Deep water

N  


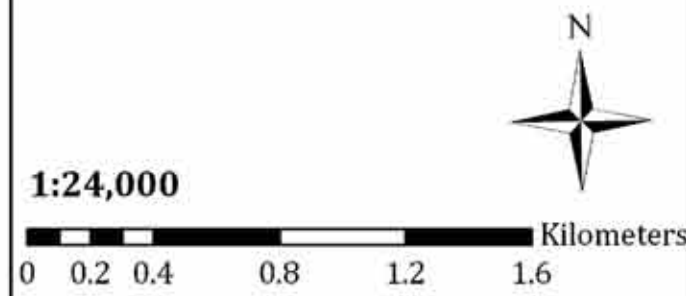
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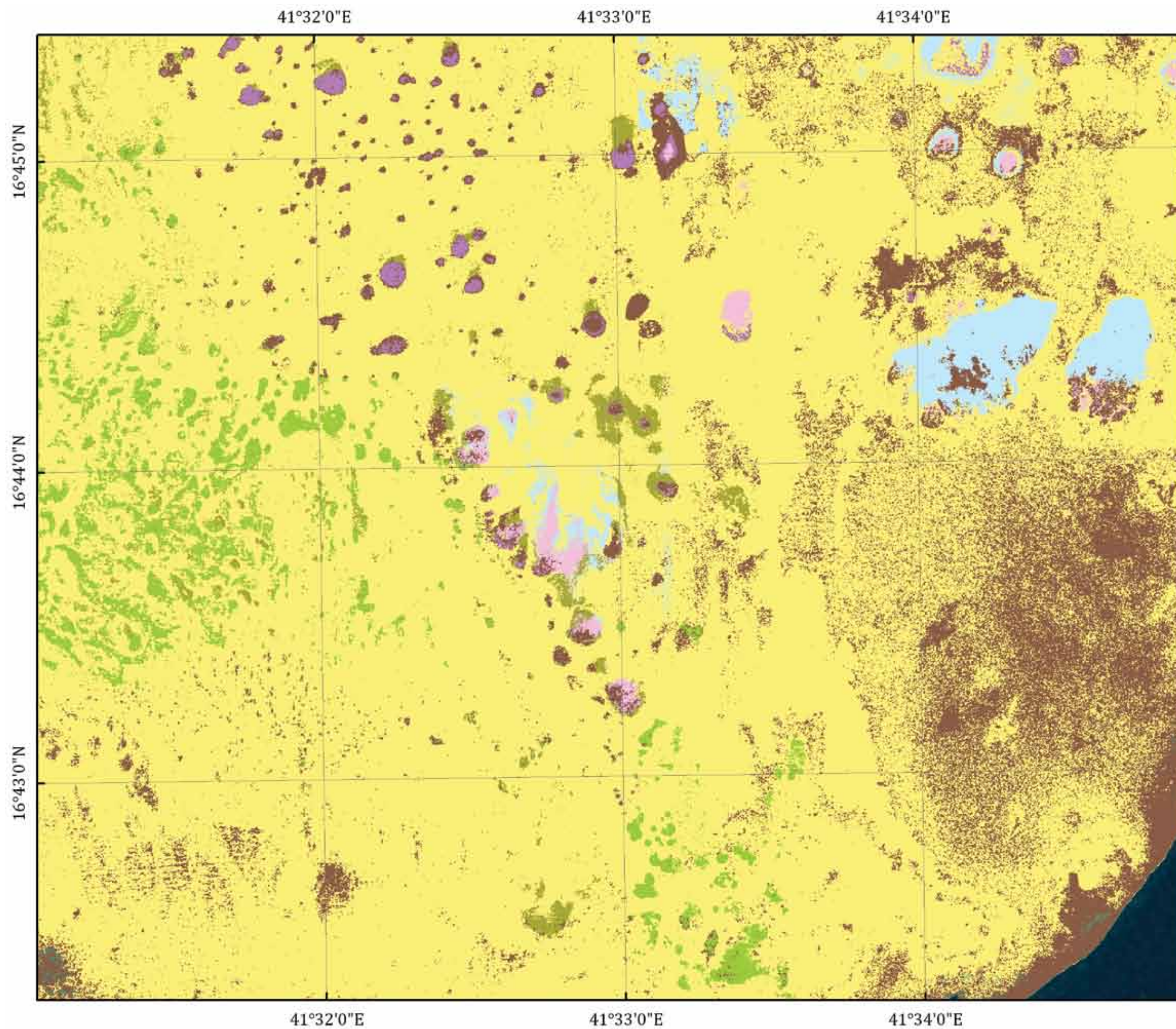
 Kilometers  
 0 0.2 0.4 0.8 1.2 1.6



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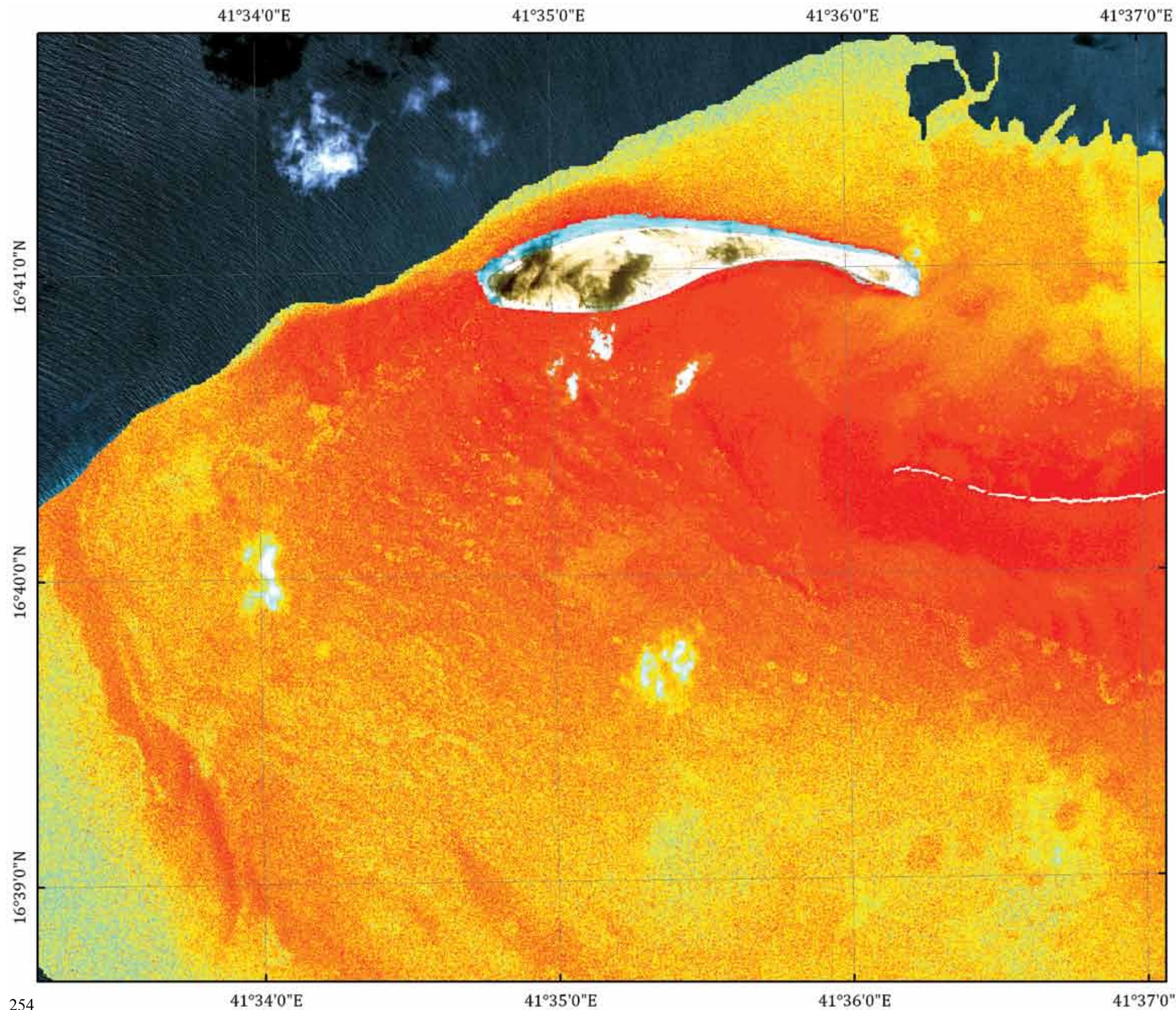


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1:24,000





**Farasan Islands Bathymetry**

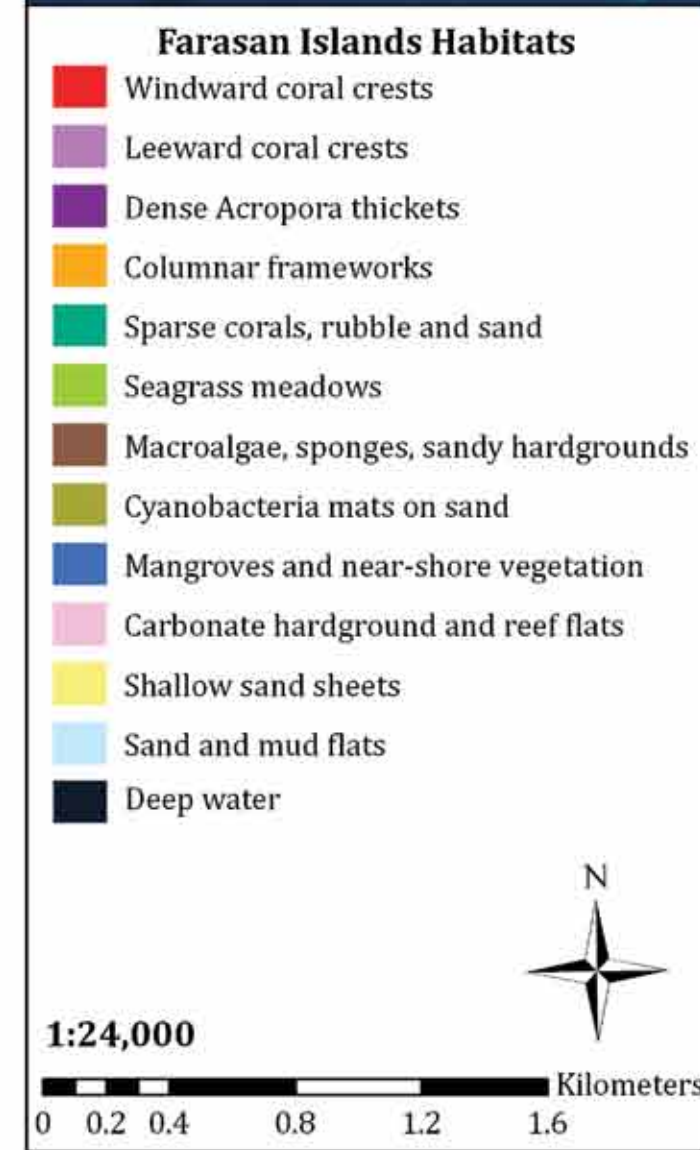
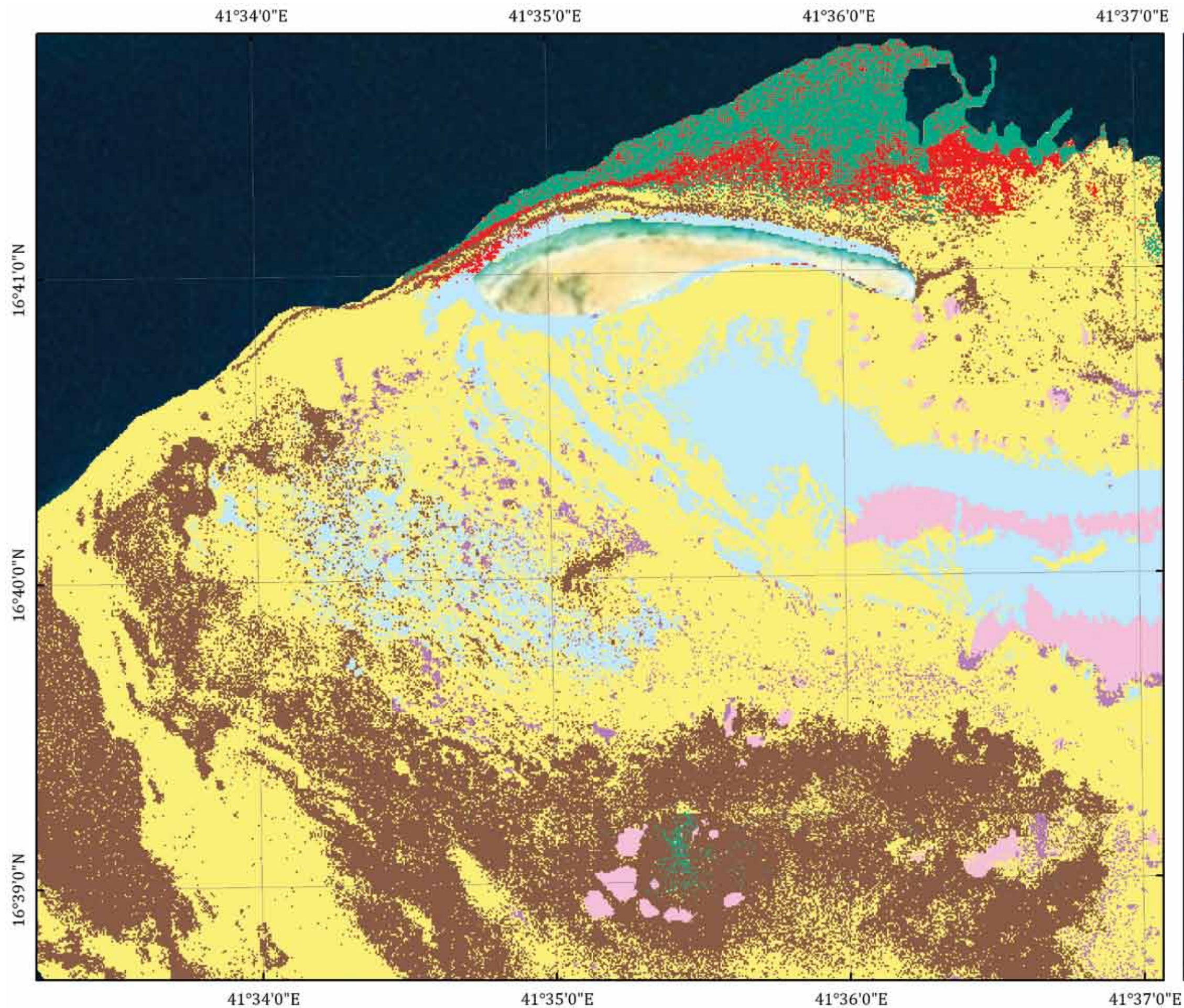
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0 - 0.9	12 - 12.9
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3 - 3.9	15 - 15.9
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7 - 7.9	19 - 19.9
8 - 8.9	20 - 20.9
9 - 9.9	Deep water
10 - 10.9	Clouds
11 - 11.9	

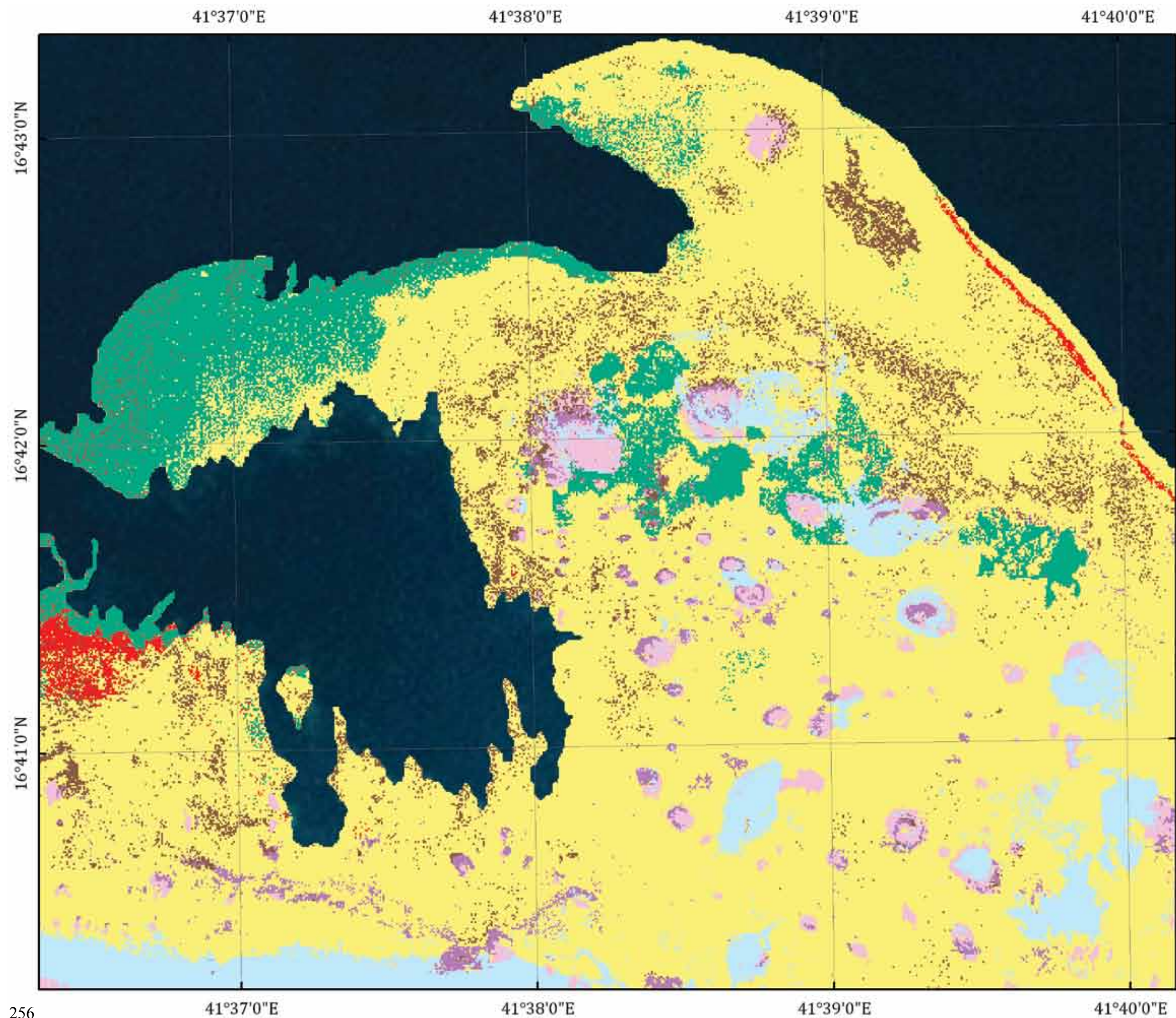


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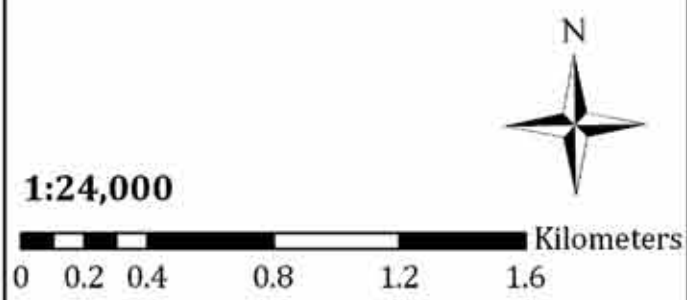


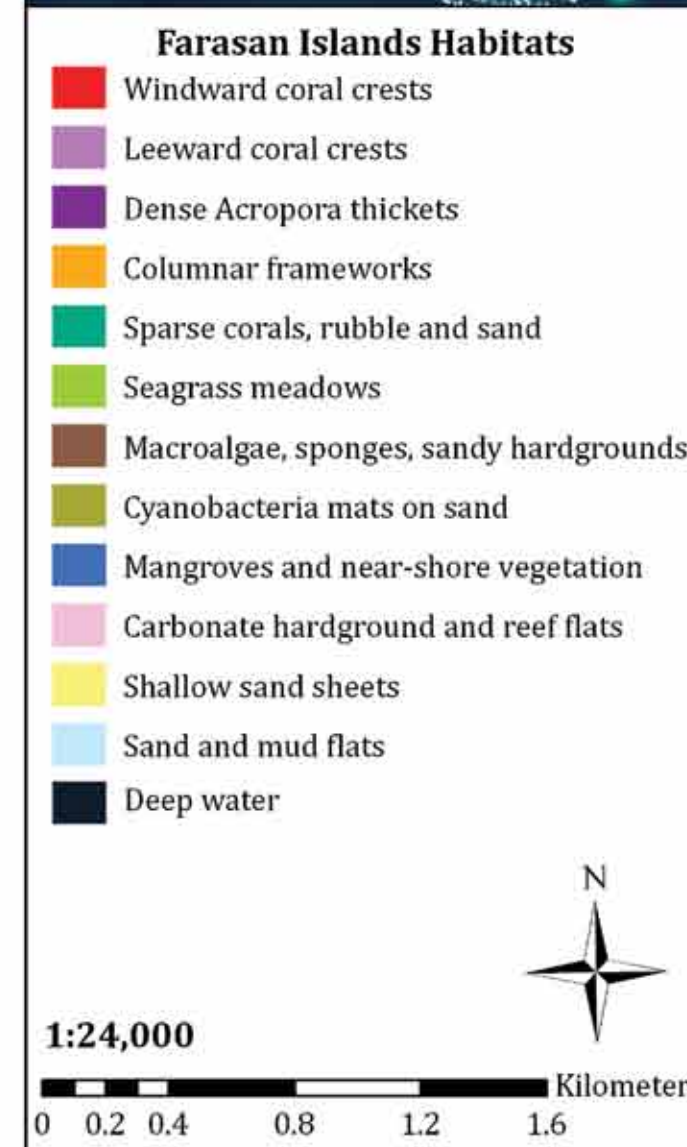
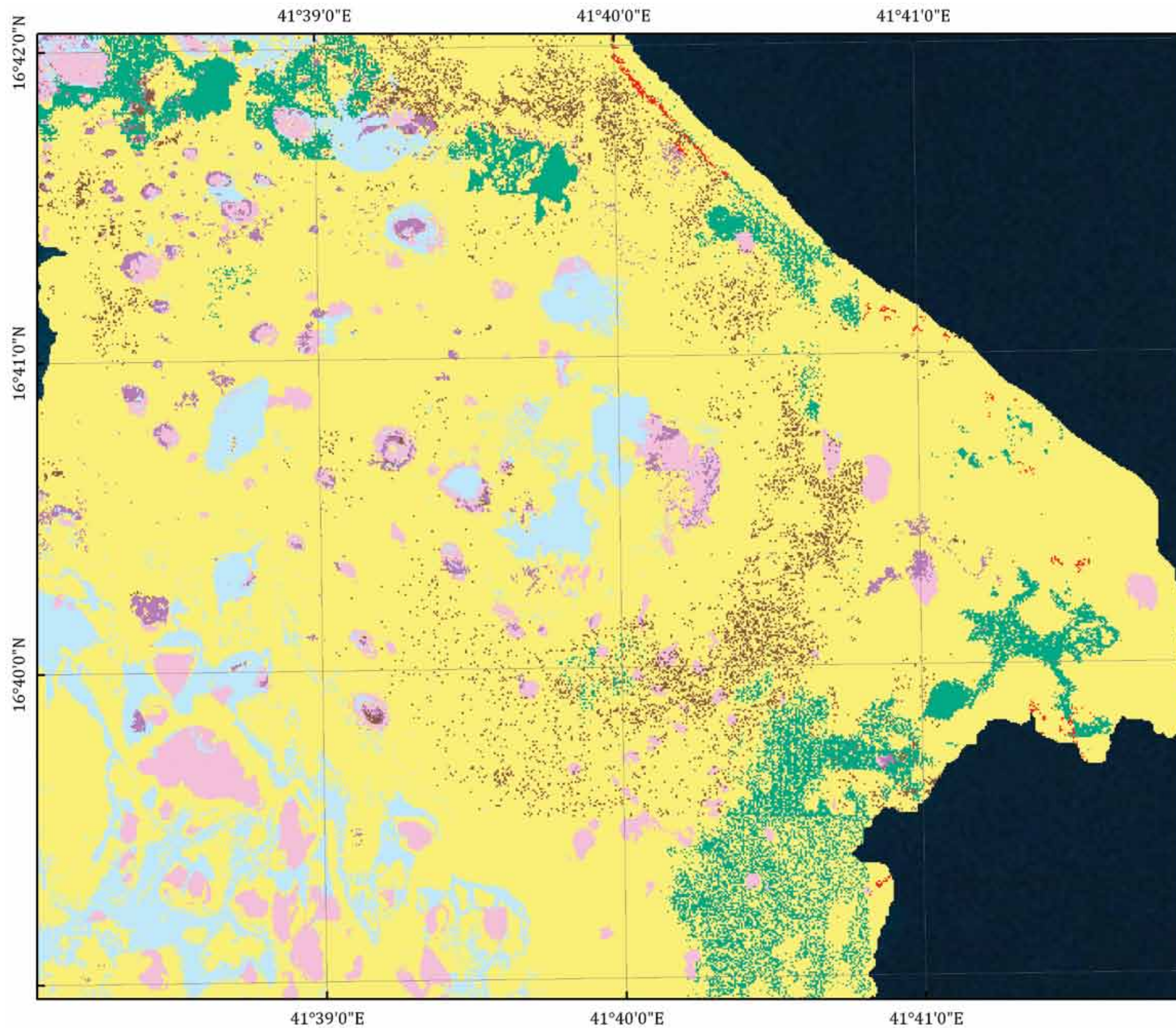


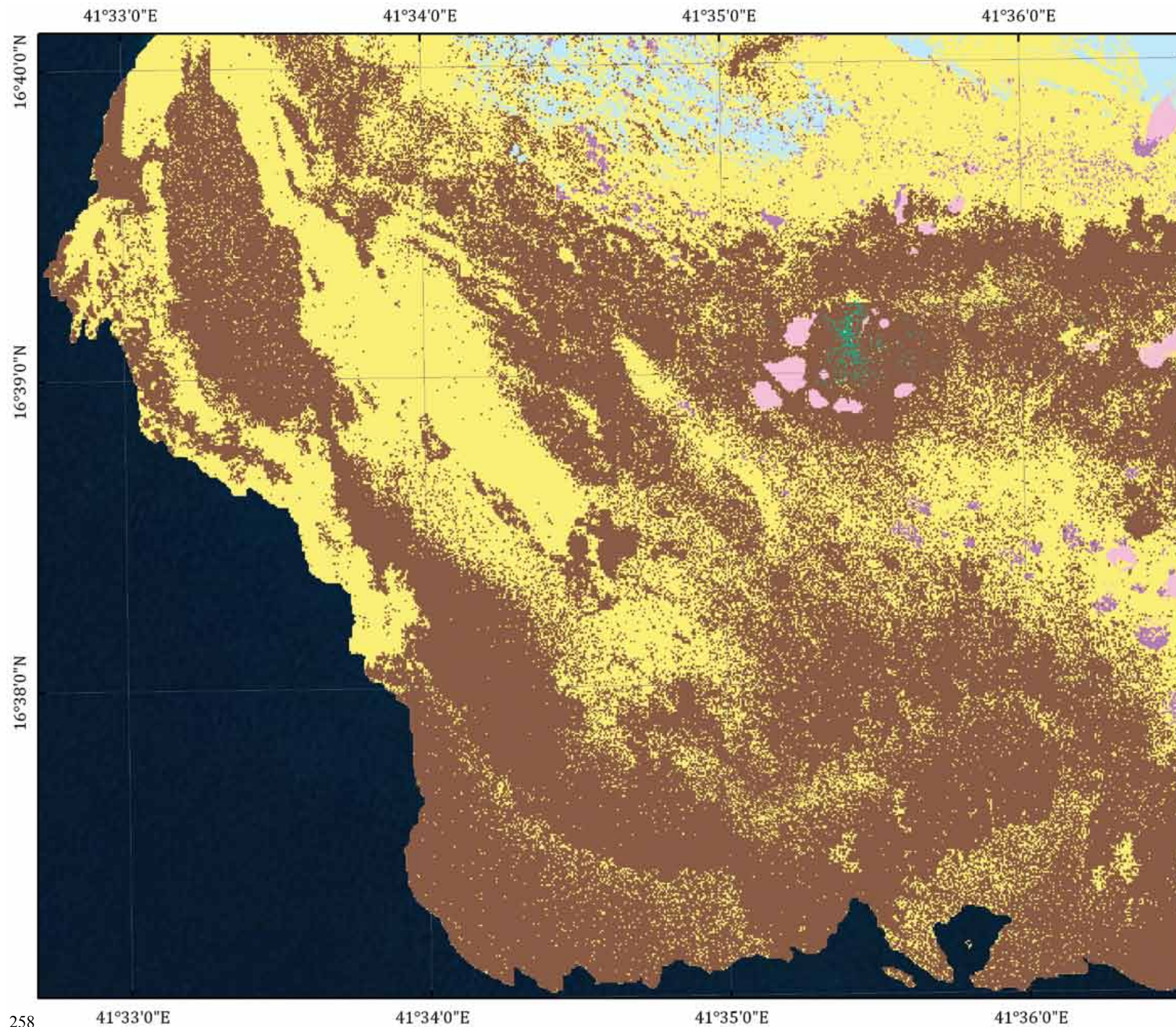


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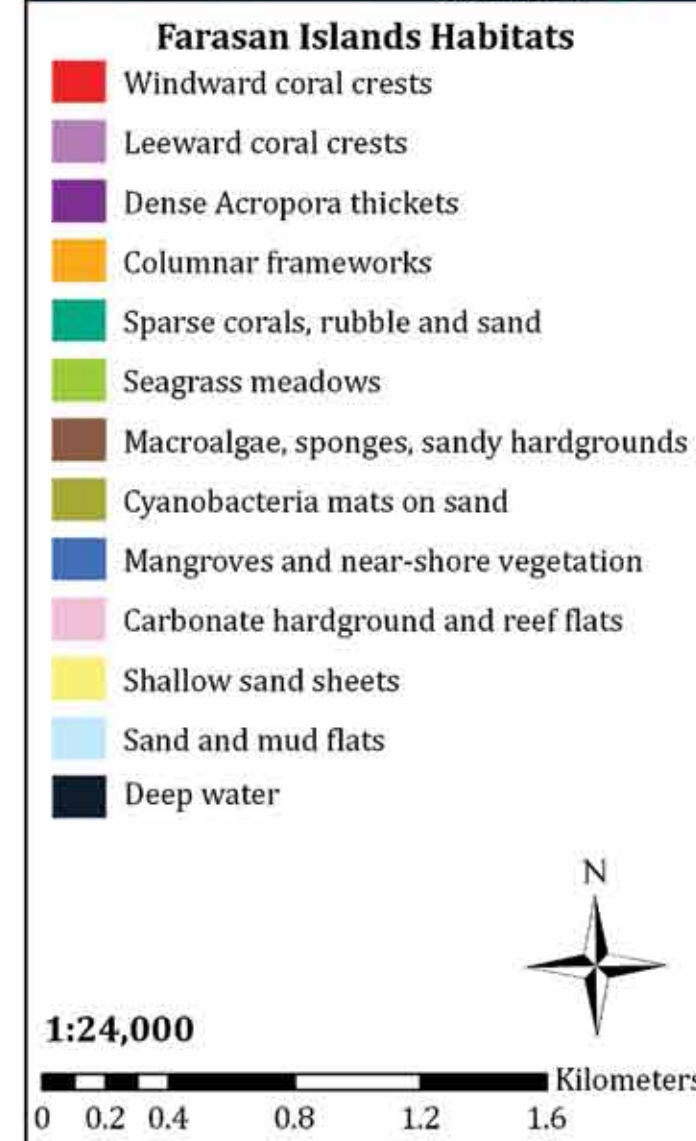
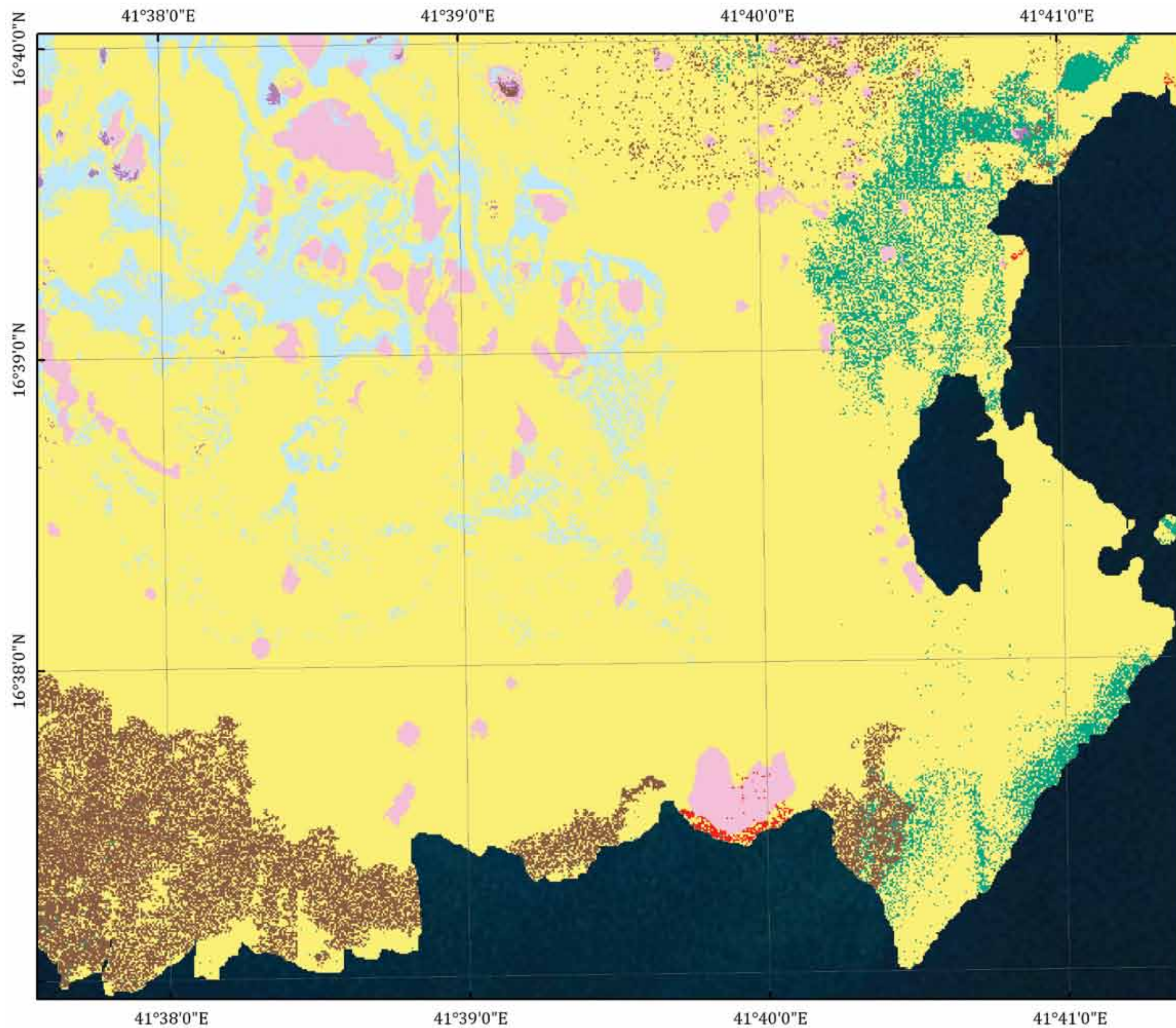
**Farasan Islands Habitats**

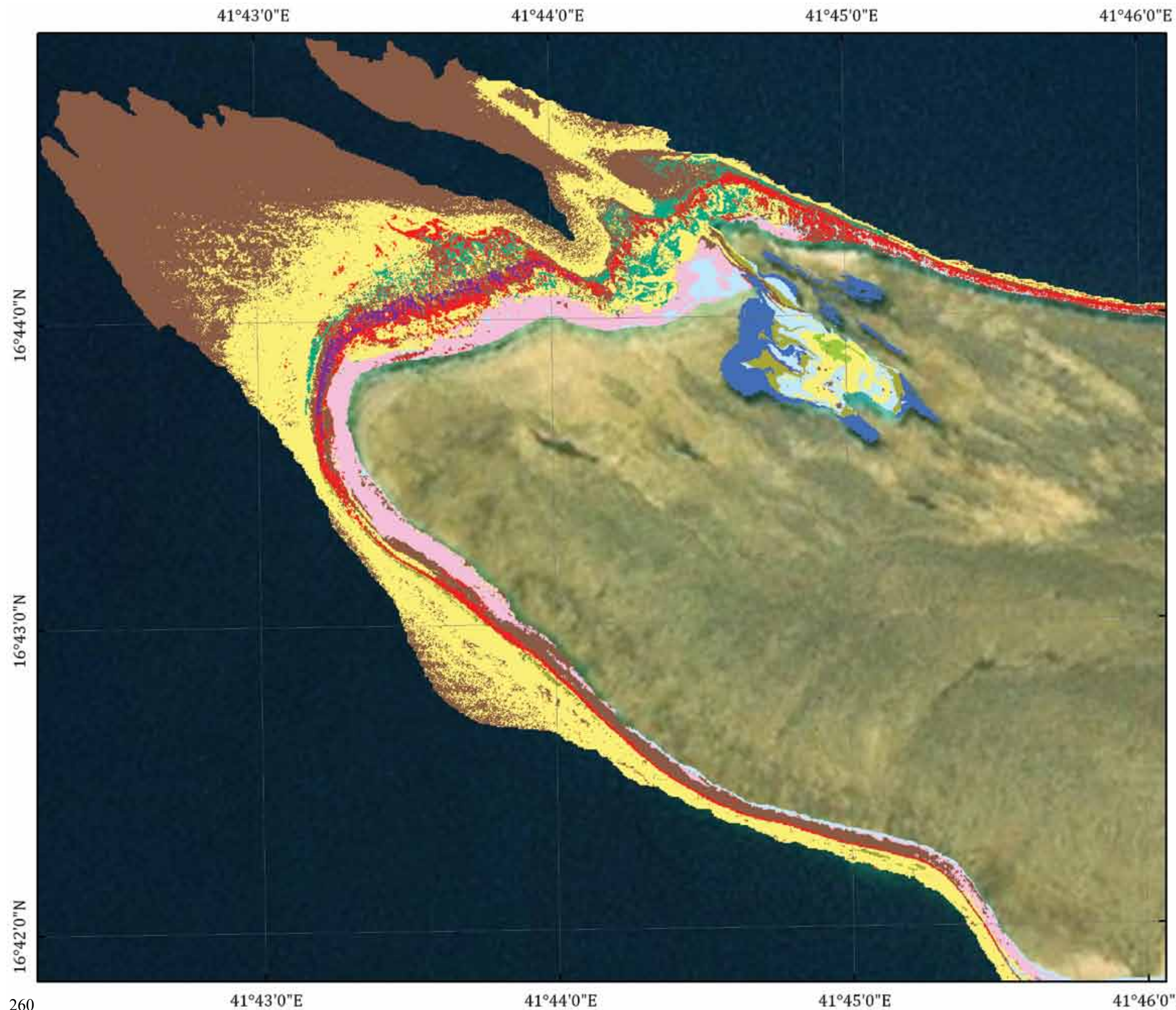
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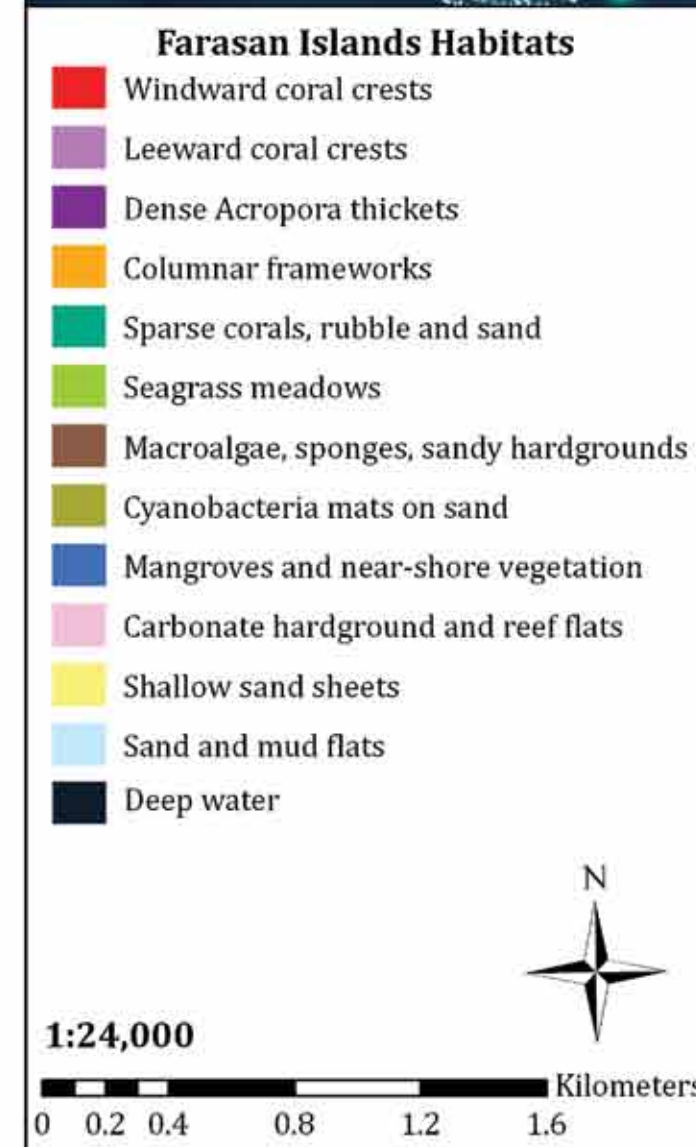
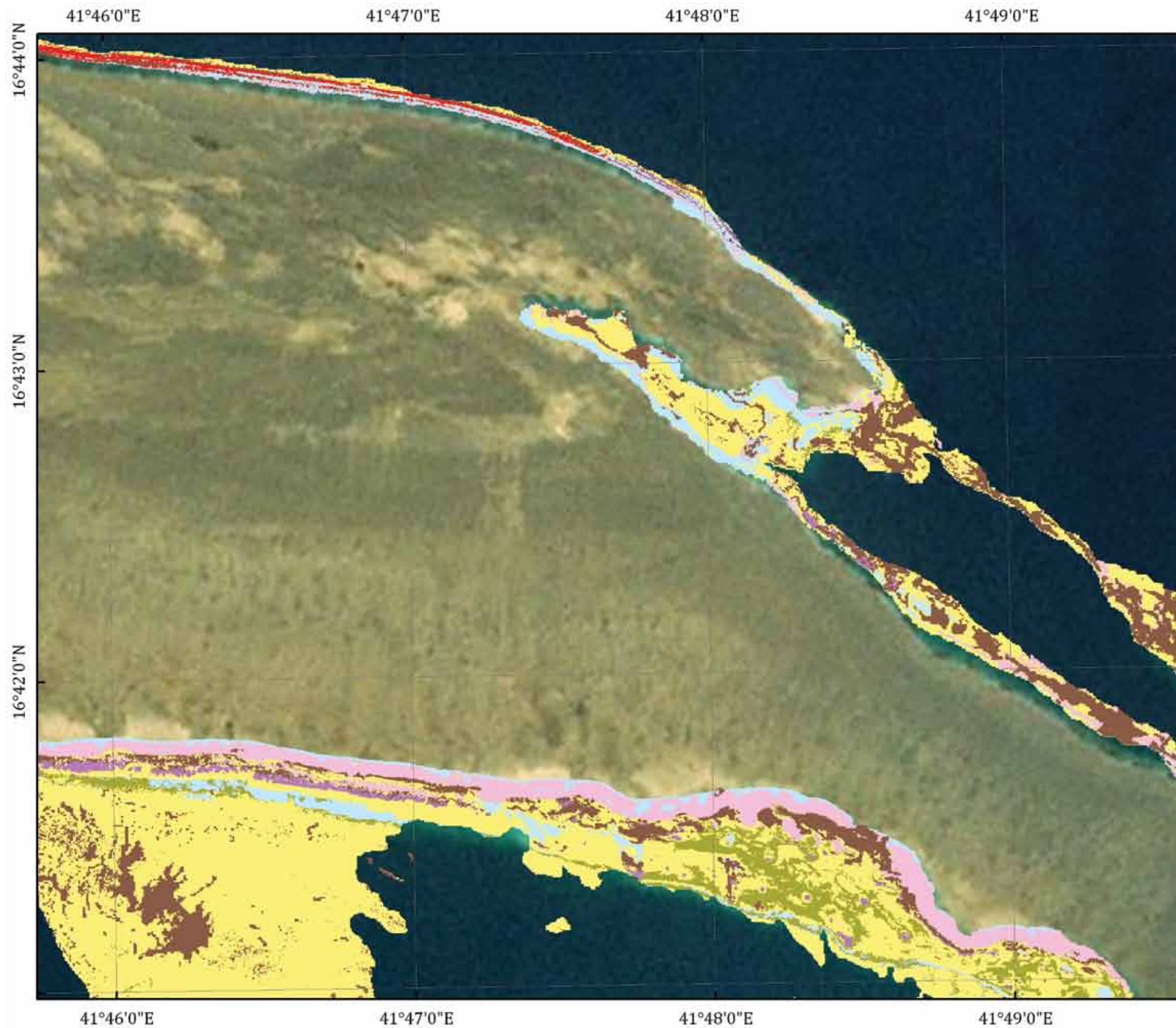
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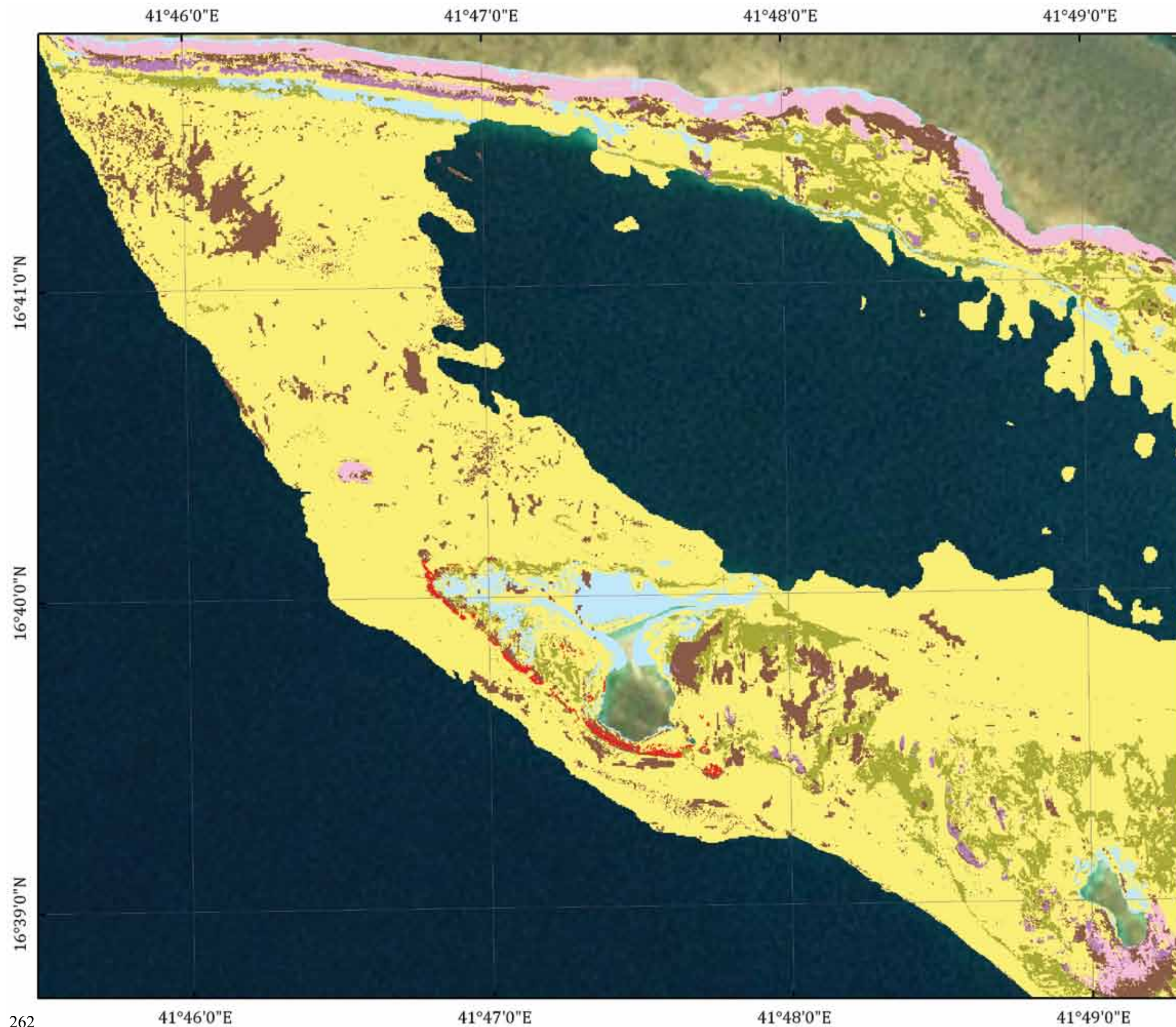
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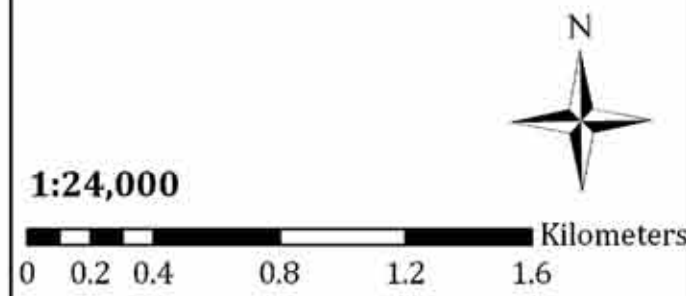


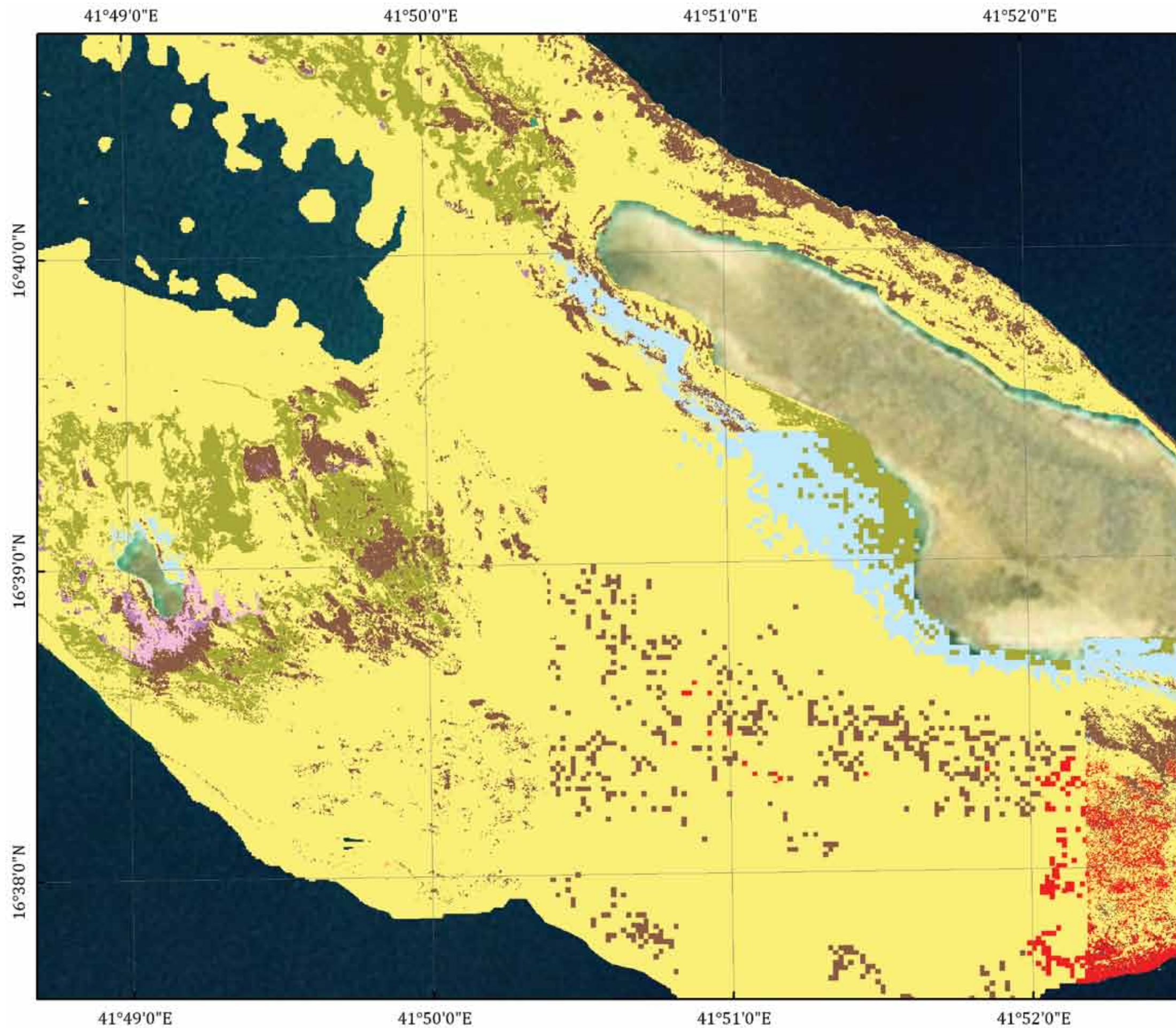




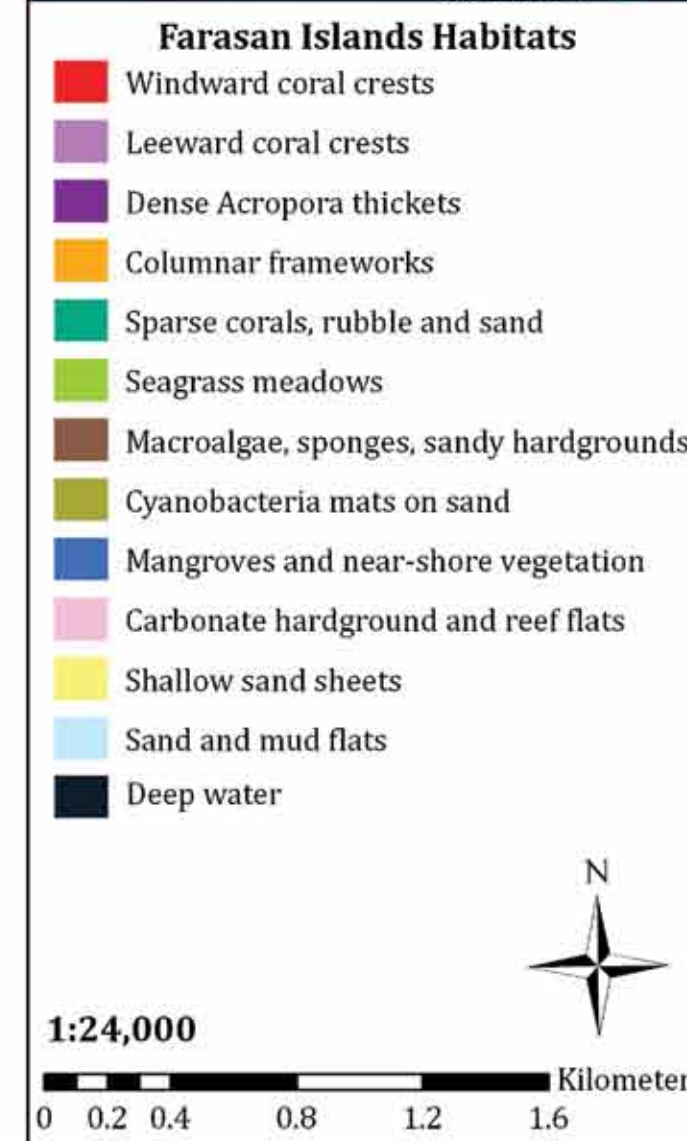
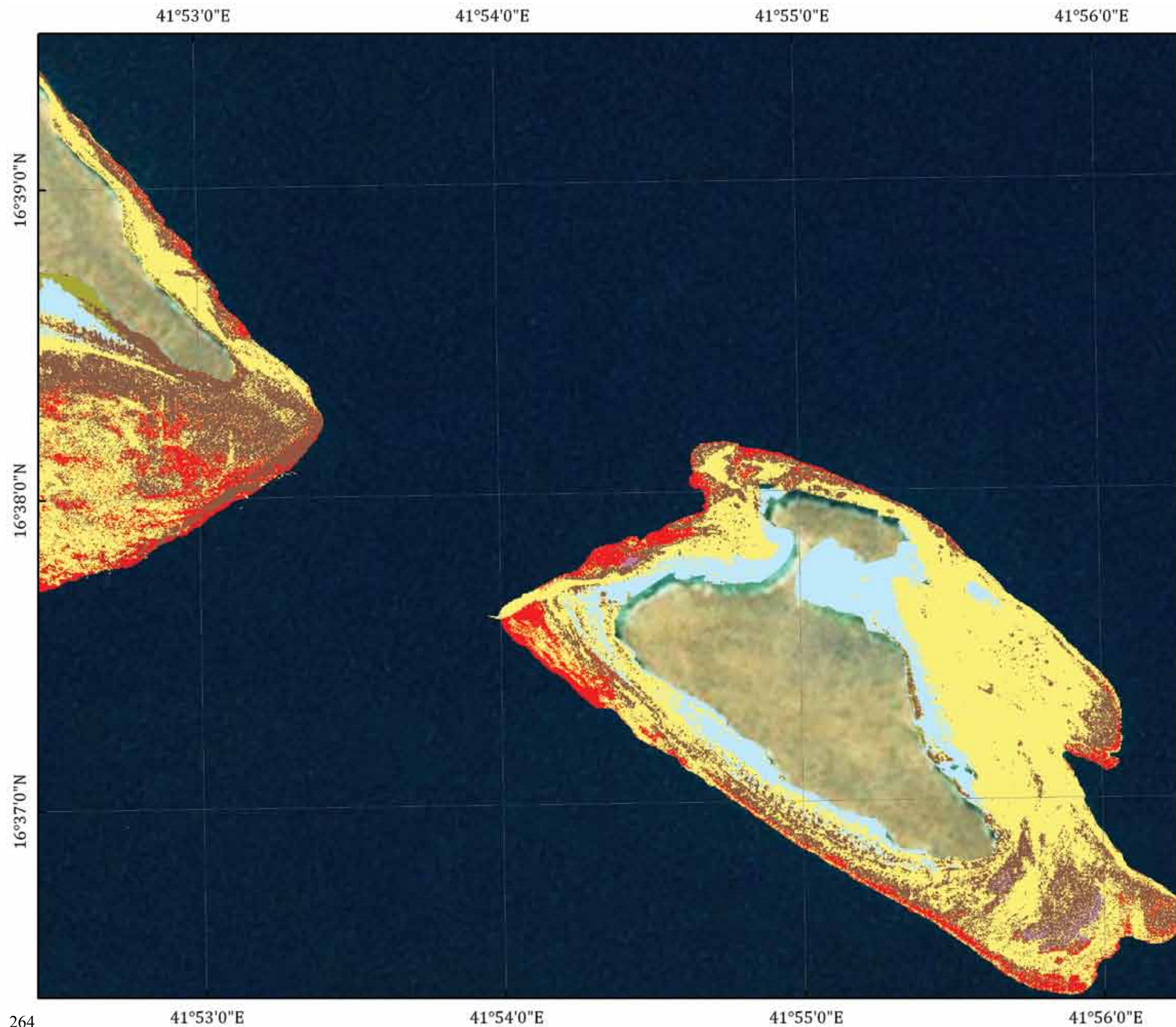
**Farasan Islands Habitats**

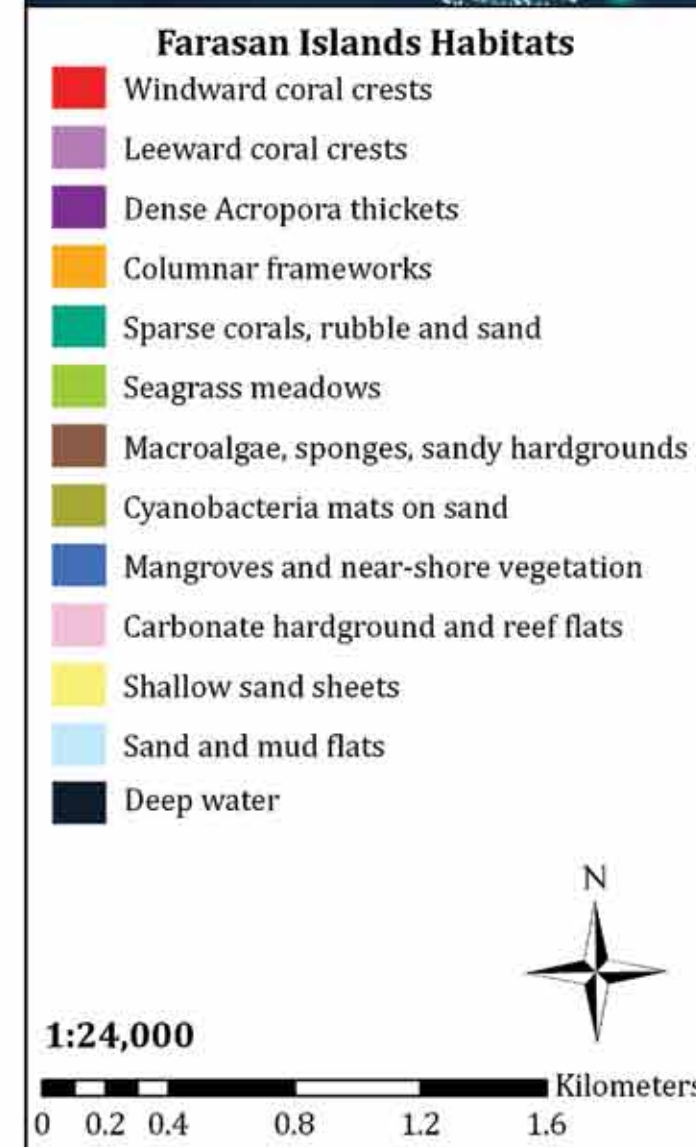
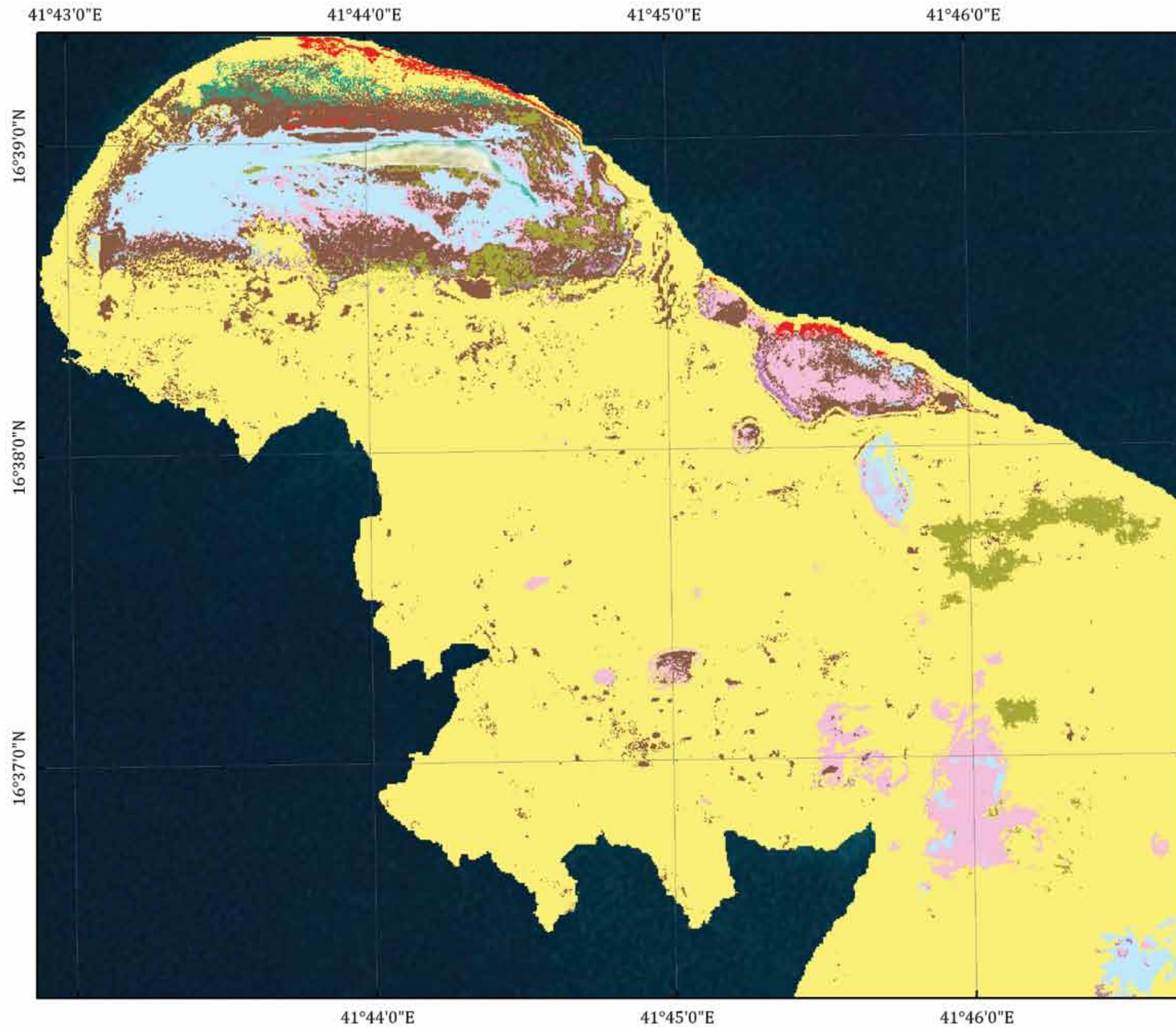
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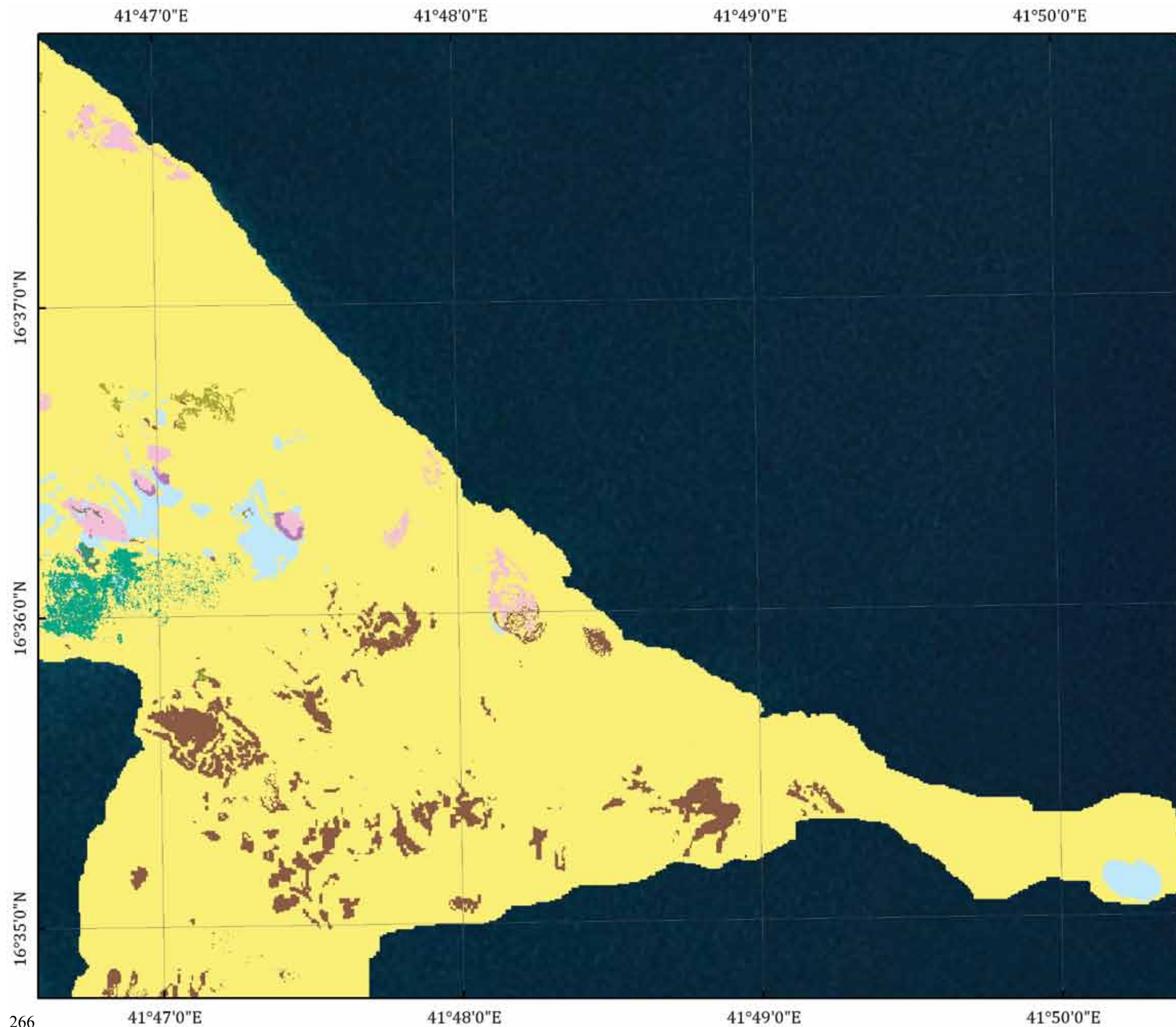






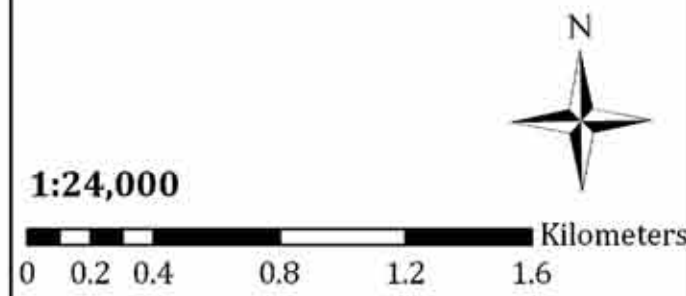


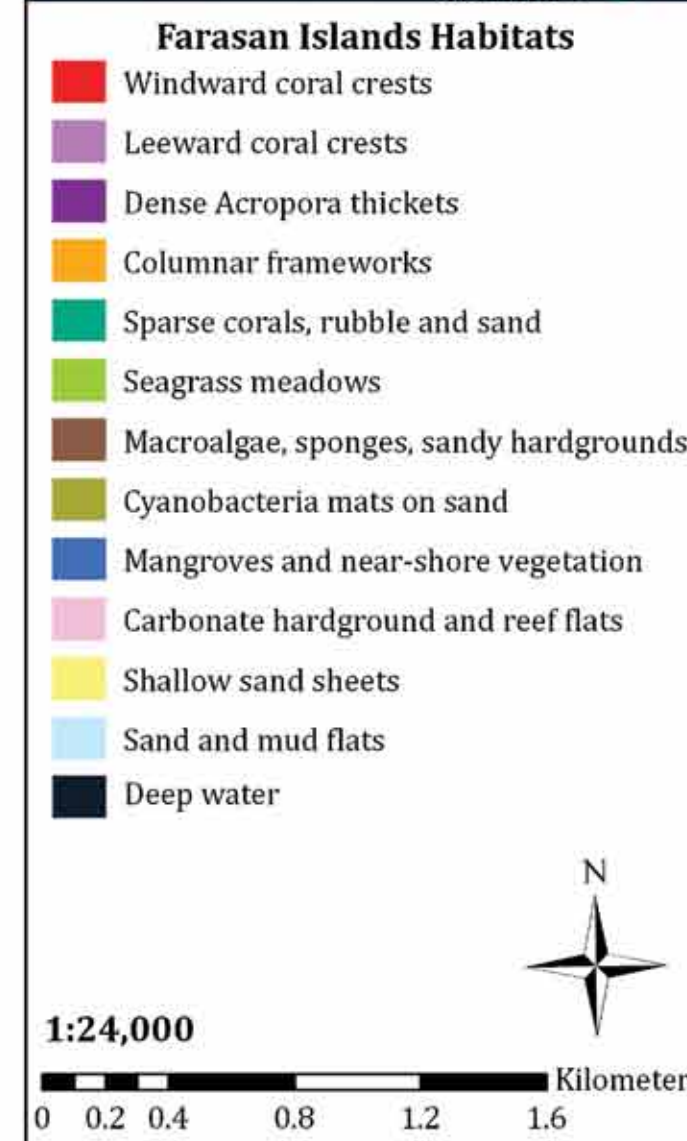
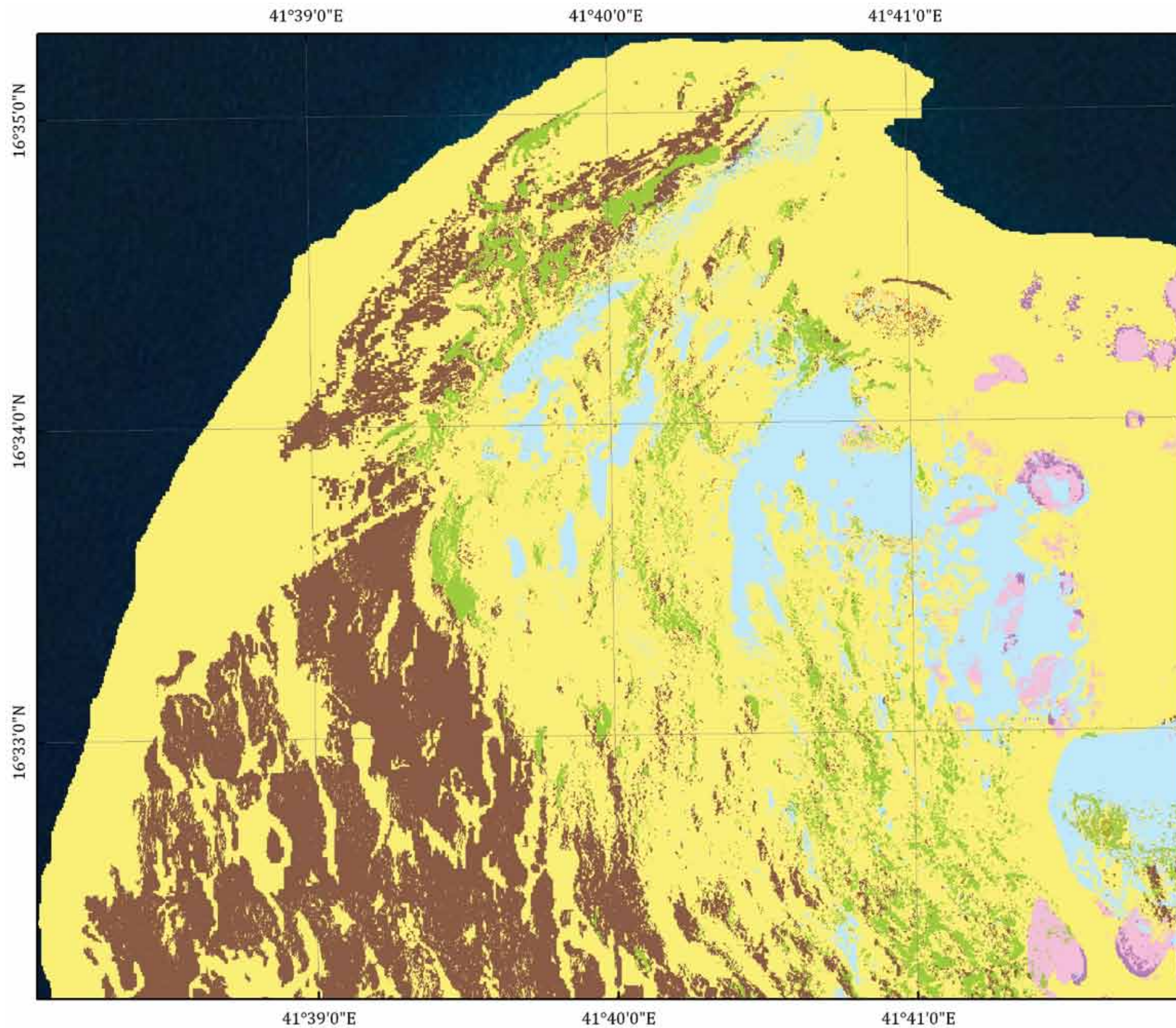


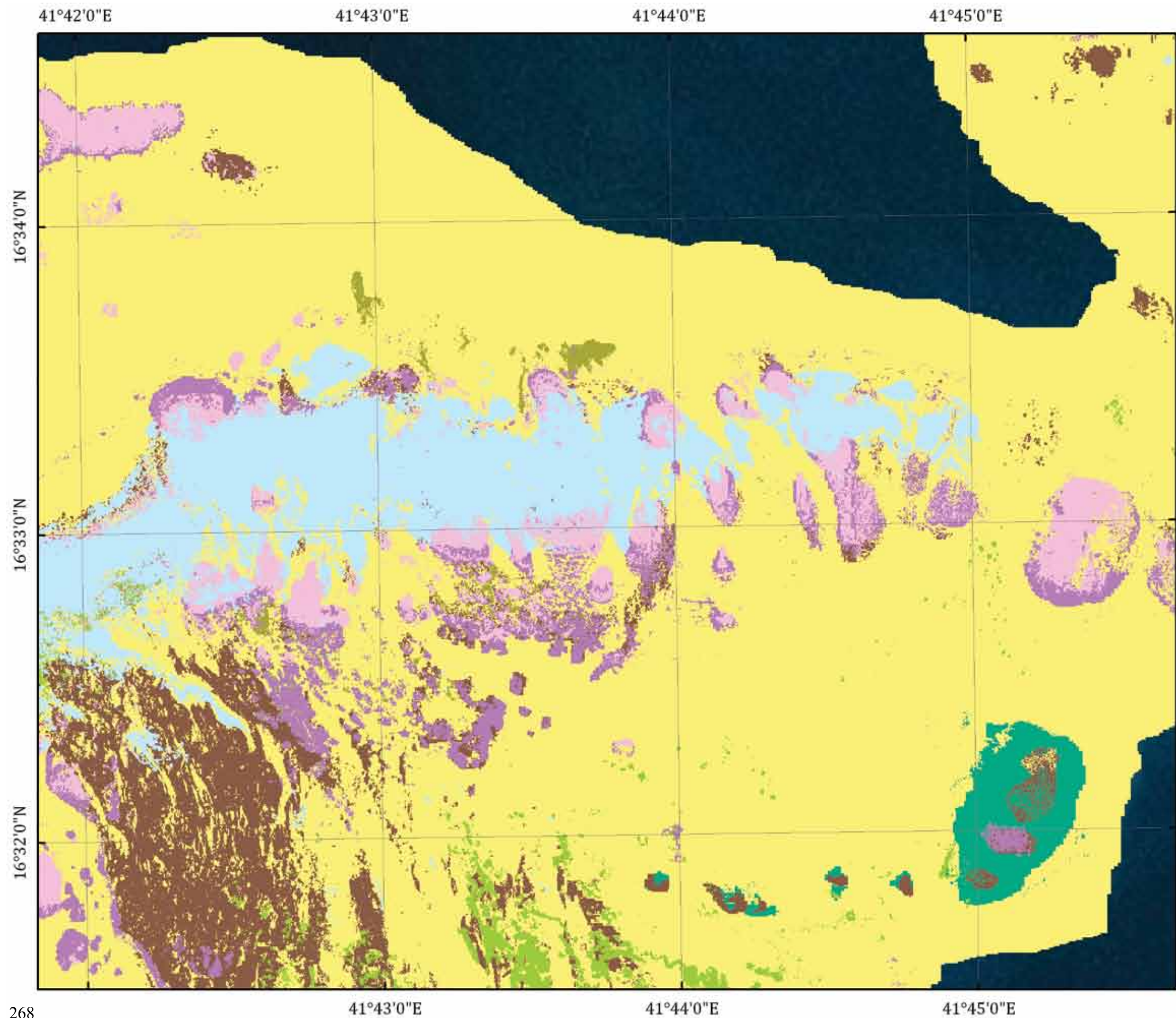


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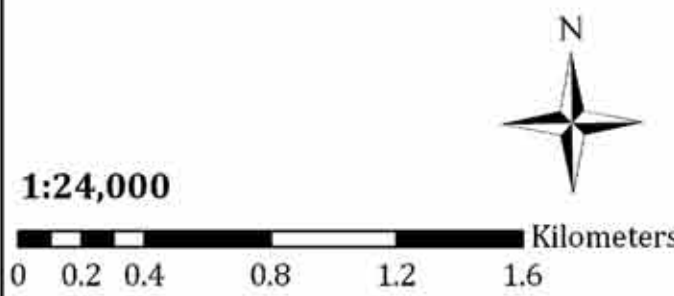


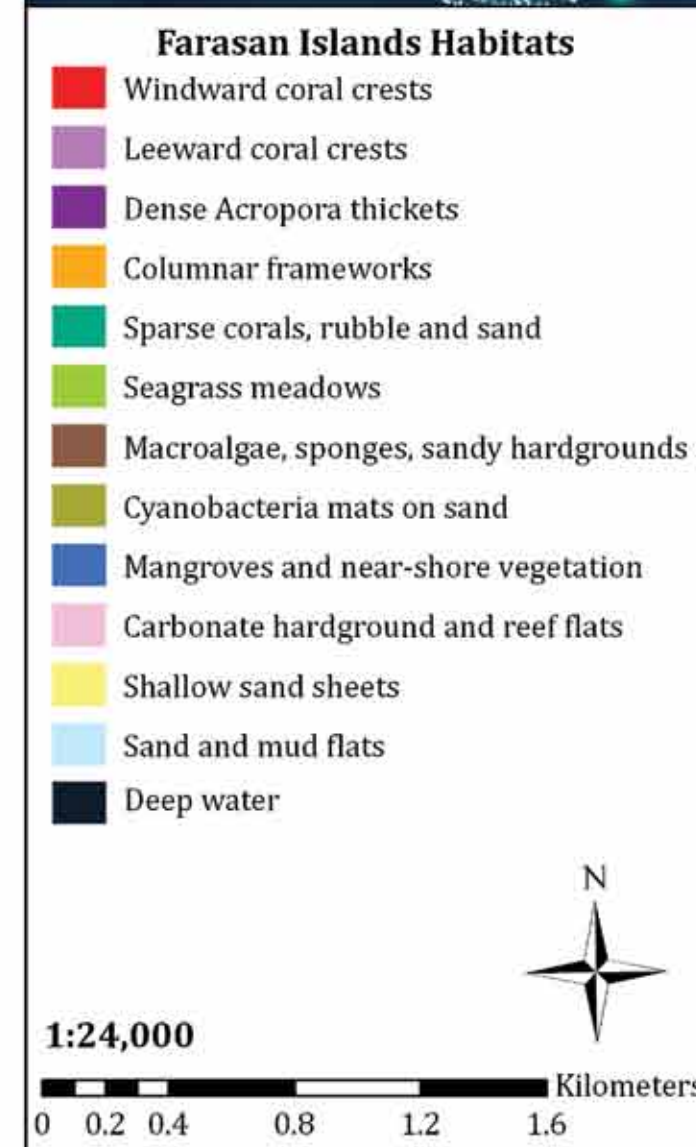
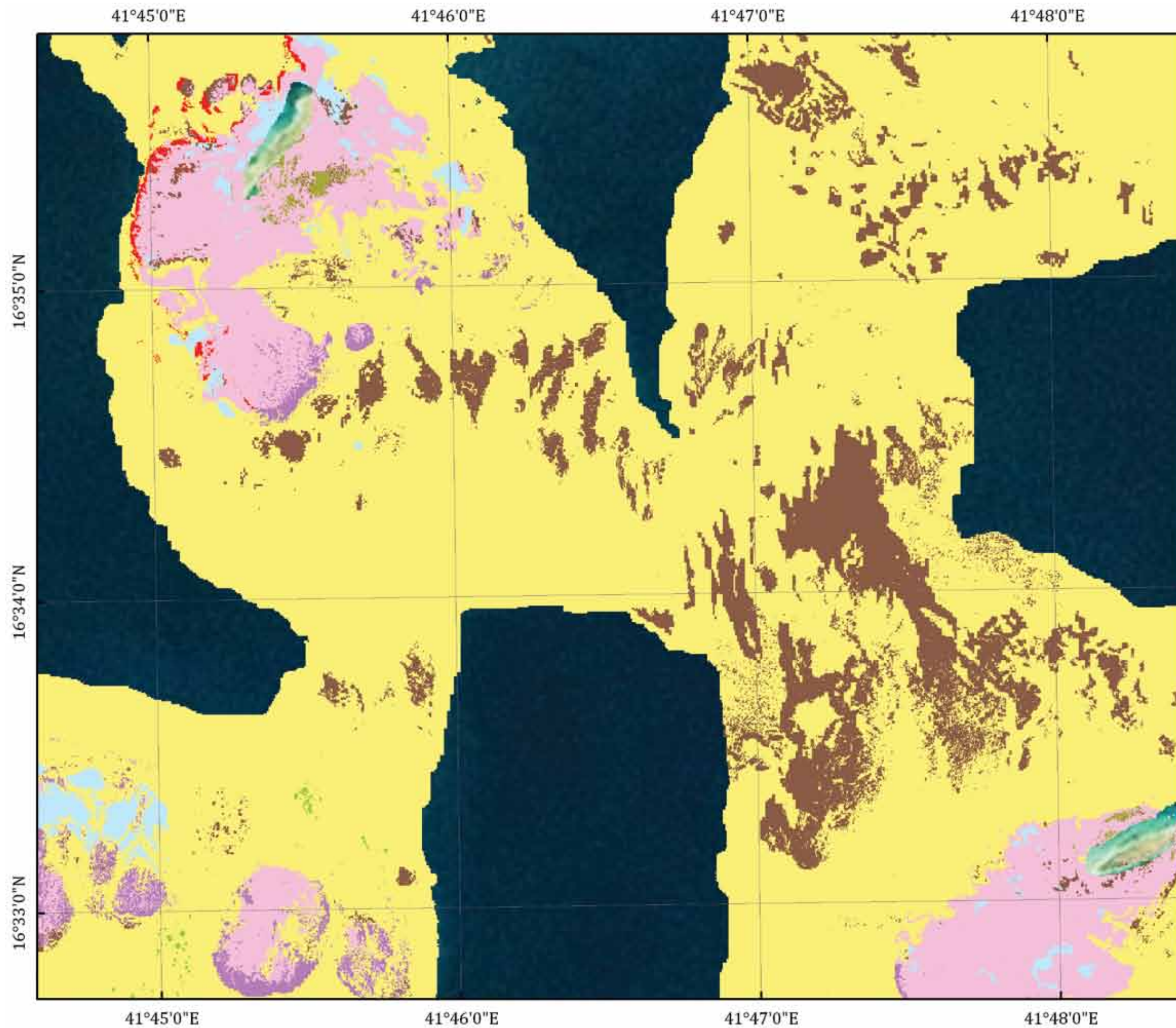


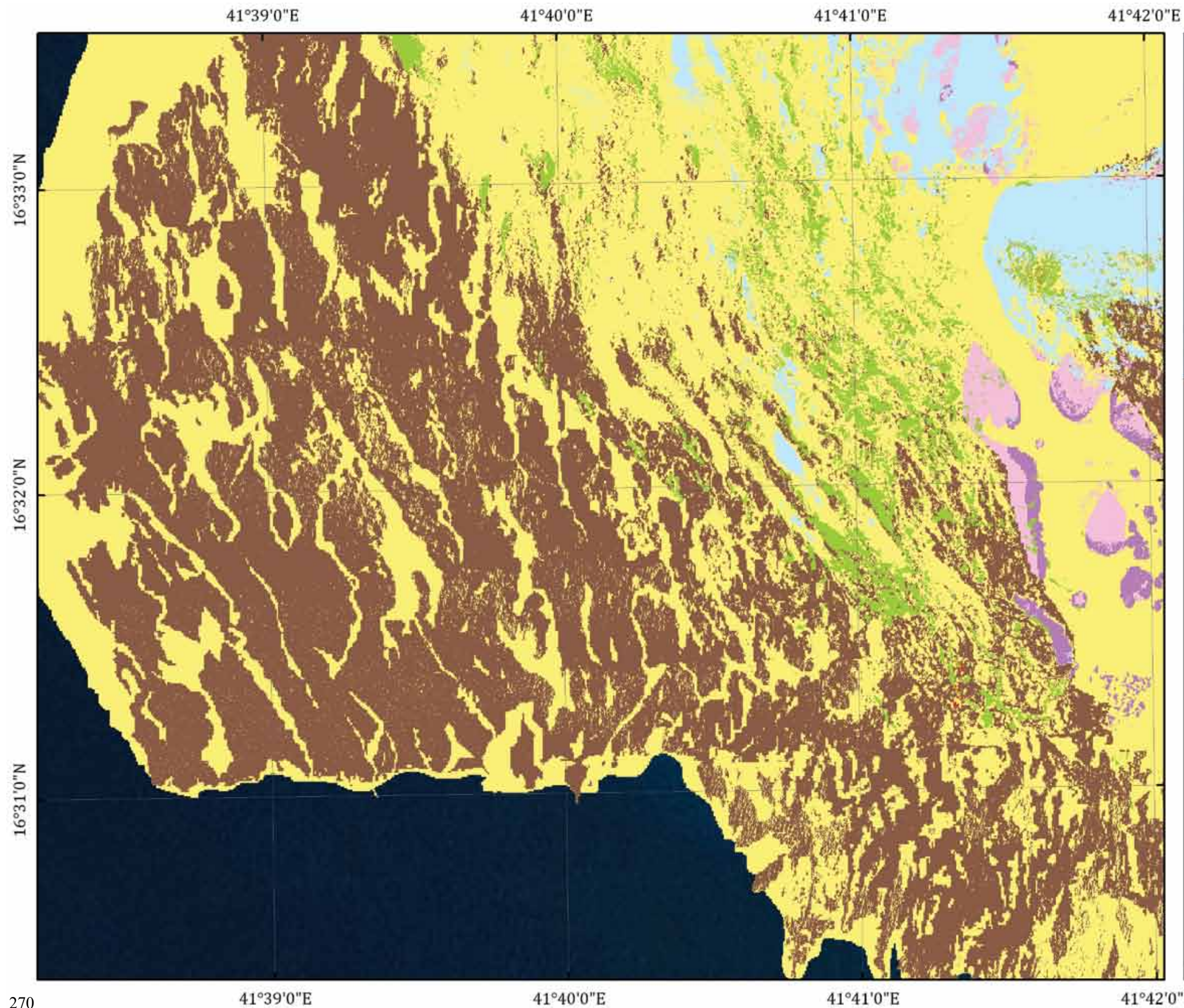


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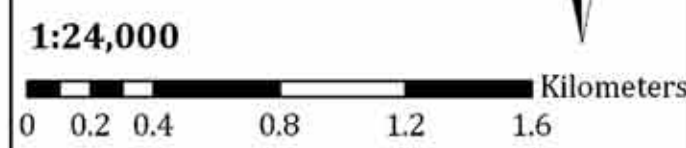


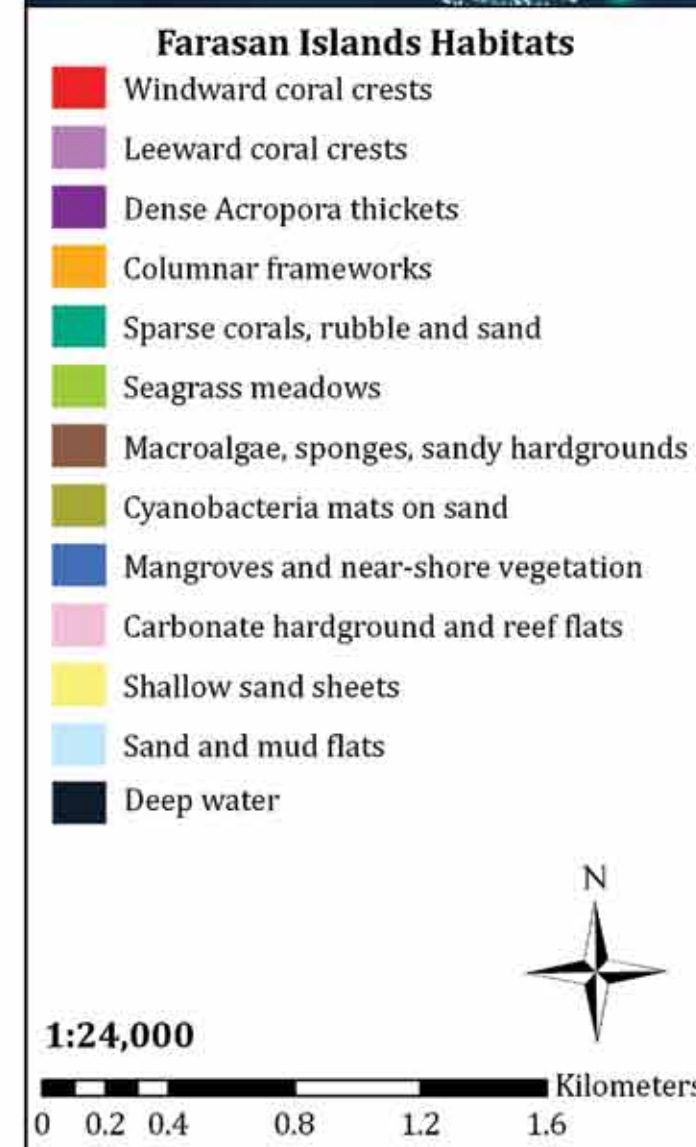
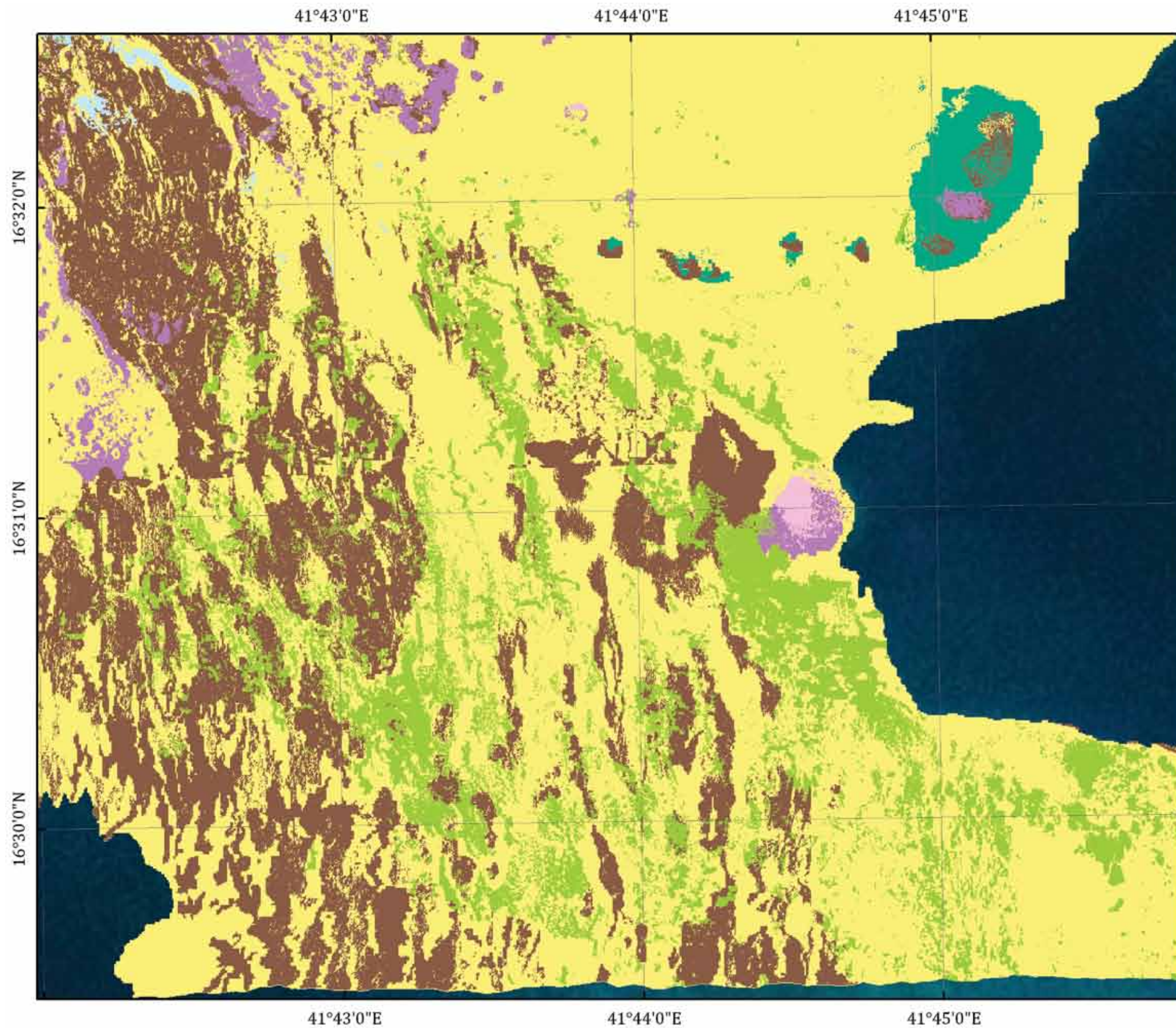




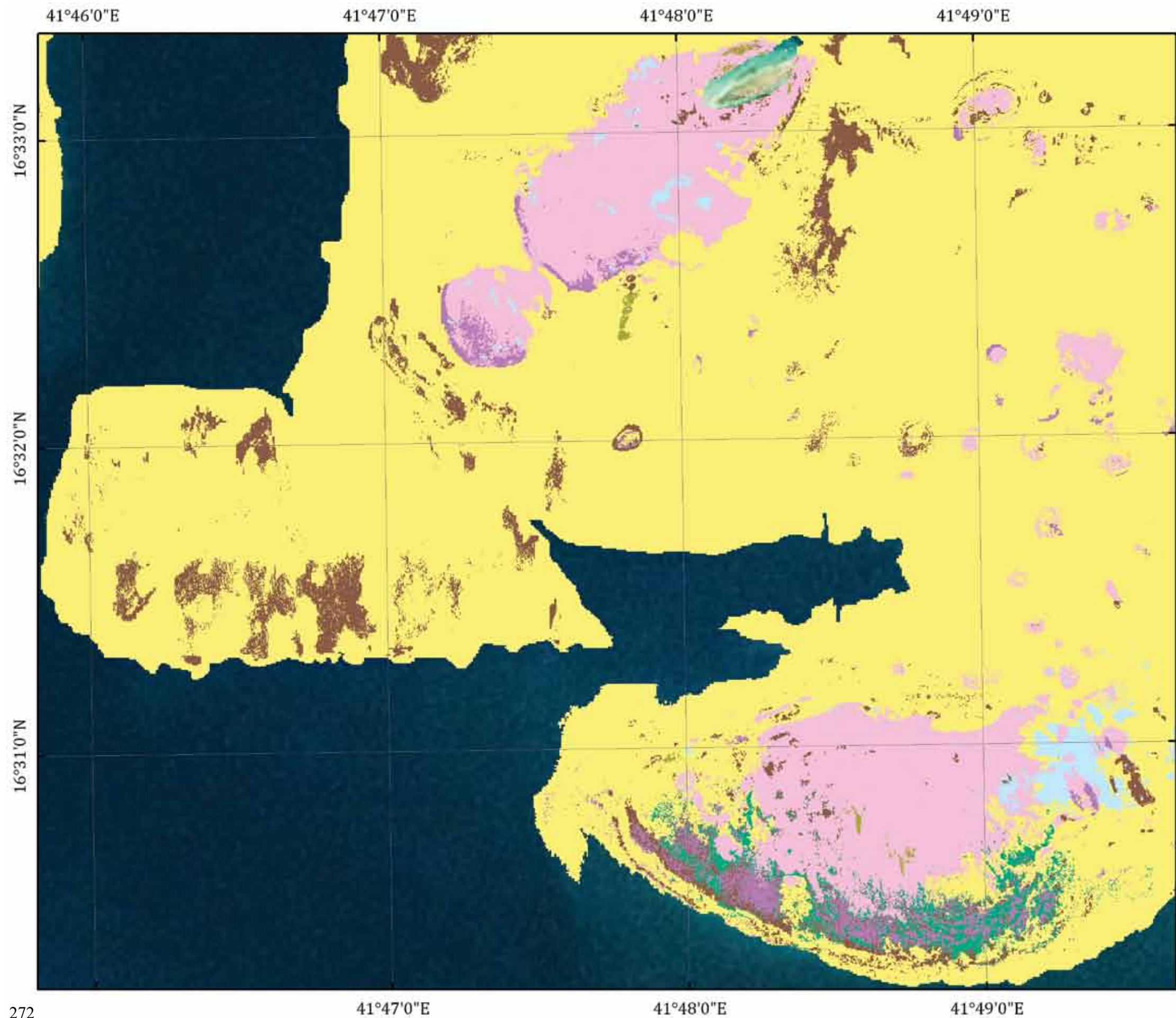
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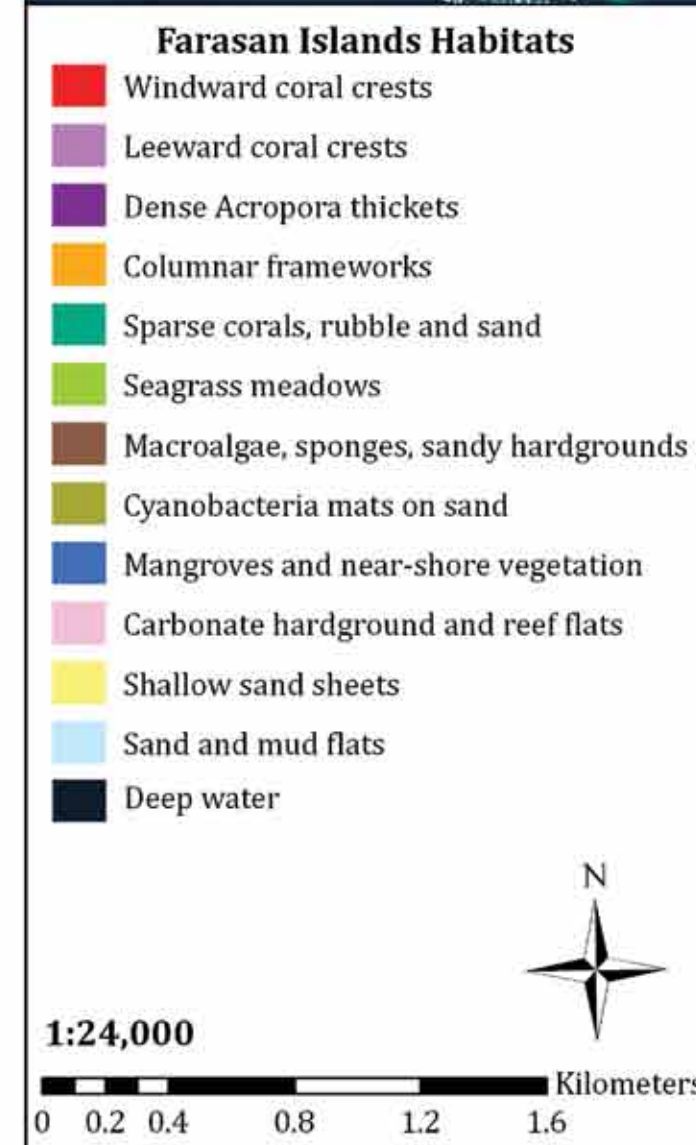
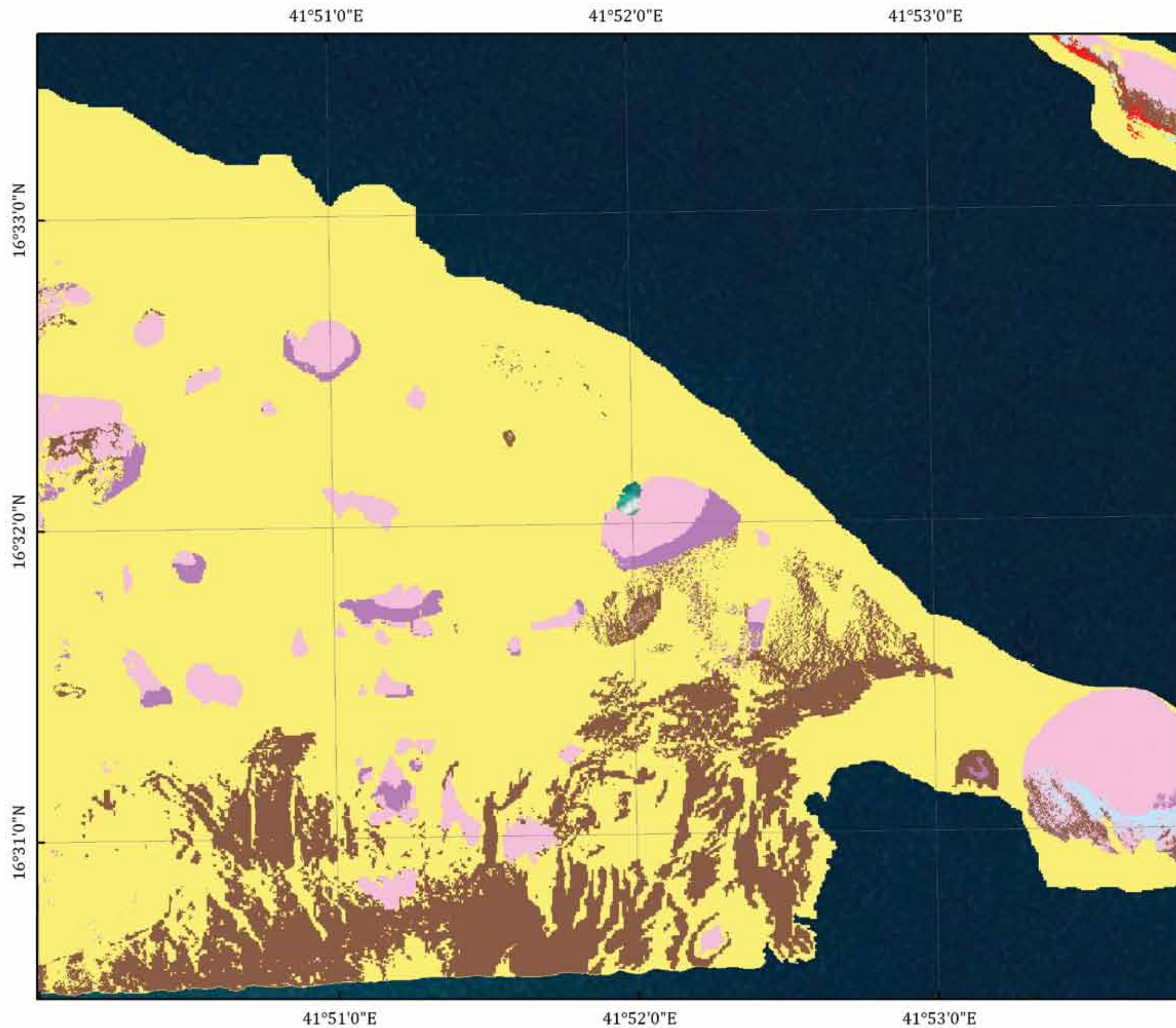
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